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Nuclear Waste Policy Act
(Section 112)

A Multiattribute U[illegible]ysis of Sites Nominated fo[illegible] Characterization fo[illegible] Radioactive-Waste [illegible] A Decision-Aiding [illegible]logy

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FOREWORD

In December 1984, the Department of Energy (DOE) published draft environmental assessments (EAs) to support the proposed nomination of five sites and the recommendation of three sites for characterization for the first radioactive-waste repository. A chapter common to all the draft EAs (Chapter 7) presented rankings of the five sites against the postclosure and the preclosure technical siting guidelines. To determine which three sites appeared most favorable for recommendation for characterization, three simple quantitative methods were used to aggregate the rankings assigned to each site for the various technical guidelines. In response to numerous comments on the methods, the DOE has undertaken a formal application of one of them (hereafter referred to as the decision-aiding methodology) for the purpose of obtaining a more rigorous evaluation of the nominated sites.

The application of the revised methodology is described in this report. The method of analysis is known as multiattribute utility analysis; it is a tool for providing insights as to which sites are preferable and why. The decision-aiding methodology accounts for all the fundamental considerations specified by the siting guidelines and uses as source information the data and evaluations reported or referenced in the EAs. It explicitly addresses the uncertainties and value judgments that are part of all siting problems. Furthermore, all scientific and value judgments are made explicit for the reviewer. An independent review of the application of the decision-aiding methodology has been conducted by the Board on Radioactive Waste Management of the National Academy of Sciences; the comments of the Board are included as an appendix to this report.

In spite of its advantages, the formal analysis cannot address every aspect of the site-recommendation decision and thus its results will not form the sole basis for that decision. The site-recommendation decision is analogous to a portfolio-selection problem because the DOE is not choosing a single site for repository development; rather, the DOE must choose, from a suite of five well-qualified sites, three sites for site characterization. Combinations of three sites possess properties that cannot be attributed to individual sites, such as diversity of geohydrologic settings and rock types. Thus, the three sites indicated as most preferable by the multiattribute utility analysis reported here do not necessarily constitute the most preferred combination when these portfolio effects are taken into account. The relative advantages of other combinations of three sites as portfolios together with other information the Secretary of Energy believes is important to making the decision are examined in a separate report.

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Chapter 1

BACKGROUND AND INTRODUCTION

1.1 BACKGROUND INFORMATION

The Department of Energy (DOE), pursuant to the Atomic Energy Act of 1954 as amended, the Energy Reorganization Act of 1974, the Department of Energy Organization Act of 1977, and the Nuclear Waste Policy Act of 1982 (the Act), has the responsibility to provide for the disposal of high-level radioactive waste and spent nuclear fuel.* The DOE selected mined geologic repositories as the preferred means for the disposal of commercially generated high-level radioactive waste and spent fuel (Federal Register, Vol. 46, p. 26677, May 14, 1981) after evaluating various means for the disposal of these materials and issuing an environmental impact statement. To carry out this decision, the DOE has been conducting research and development and performing siting studies.

The Act established a process and schedule for siting two geologic repositories by integrating the then-existing DOE siting program into its requirements and procedures. As explained later in this chapter, the Act requires the Secretary of Energy to nominate not fewer than five sites as suitable for site characterization and subsequently to recommend three of the nominated sites to the President as candidate sites for characterization. Site characterization will involve the collection of detailed information on the geologic, hydrologic, and other characteristics of the site that determine compliance with the requirements of the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC). It will involve the construction of exploratory shafts to the depth at which a repository would be built and in-situ testing. In parallel with these subsurface investigations, the DOE will collect information on the demographic, socioeconomic, and ecological characteristics of the affected areas containing the sites approved for site characterization. These subsurface and surface investigations are expected to cost upward of 500 million dollars per site.

This report presents a formal analysis of the five sites nominated as suitable for characterization for the first repository; the analysis is based on the information contained or referenced in the environmental assessments that accompany the site nominations (DOE, 1986a-e). It is intended to aid in

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*High-level radioactive waste means (1) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations and (2) other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation. For convenience, the terms "radioactive waste" and "waste" are used for both spent fuel and high-level radioactive waste.

the site-recommendation decision by providing insights into the comparative advantages and disadvantages of each site. Because no formal analysis can account for all the factors important to a decision as complex as recommending sites for characterization, this study will not form the sole basis for that decision. To help the reader understand the context of the formal study and of subsequent decisions, the remainder of this chapter presents additional background information on the geologic repository concept, the Act, and the DOE siting process, before and after the passage of the Act.

1.1.1 THE GEOLOGIC REPOSITORY CONCEPT

A geologic repository will be developed much like a large mine. Shafts will be constructed to allow for the removal of excavated material and to permit the construction of tunnels and disposal rooms at some depth between 1000 and 4000 feet underground. Other shafts will be constructed to allow for the transfer of waste. Surface facilities will be provided for receiving and preparing the waste for emplacement underground. The surface and underground facilities will occupy about 400 and 2000 acres of land, respectively. When the repository has been filled to capacity and its expected long-term performance has been shown to be satisfactory, the surface facilities will be decommissioned and all shafts and boreholes will be backfilled and permanently sealed.

A repository can be viewed as a system of multiple barriers, both natural and engineered, that act together to contain and isolate the waste. The engineered barriers include the waste package, the underground facility, and shaft and tunnel backfill materials. The waste package consists of the waste form, either spent nuclear fuel or solidified high-level waste, a metal containers, and perhaps a specially designed backfill material to separate the waste containers from the host rock. The waste package contributes to long-term isolation by delaying eventual contact between the waste and ground water. The underground facility consists of underground openings and backfill materials not associated with the waste package. These barriers further limit any ground-water circulation around the waste packages and impede the subsequent transport of radionuclides into the environment.

The geologic, hydrologic, and geochemical features of the site constitute natural barriers to long-term movement of radionuclides to the accessible environment. These natural barriers provide waste isolation by impeding radionuclide transport through the ground-water system to the accessible environment and possess characteristics that reduce the potential for human interference in the future.

Although the DOE plans to use engineered barriers--as required by both the NRC in 10 CFR Part 60 (NRC, 1983), and the EPA in 40 CFR Part 191 (EPA, 1985)--primary reliance is placed on the natural barriers for waste isolation. Therefore, in evaluating the suitability of sites, the use of an engineered-barrier system will be considered to the extent necessary to meet the performance requirements specified by the NRC and the EPA but will not be relied on to compensate for major deficiencies in the natural barriers.

1.1.2 THE NUCLEAR WASTE POLICY ACT OF 1982

The search for suitable repository sites has been under way for about 10 years, although preliminary screening began in the mid 1950s. With the passage of the Act, a specific process for siting and licensing repositories was established. Through provisions for consultation and cooperation as well as financial assistance, the Act also established a prominent role in the siting process for potential host States, affected Indian Tribes, and the public. To pay the costs of geologic disposal, the Act provides for a Nuclear Waste Fund through which commercial electric utility companies are charged a fee that is based on the amount of electricity they produce in nuclear power plants. The DOE's strategy for implementing the provisions of the Act is discussed in detail in the Mission Plan for the Civilian Radioactive Waste Management Program (DOE, 1985).

In February 1983, the DOE carried out the first requirement of the Act by formally identifying nine potentially acceptable sites for the first repository in the following locations (the host rock of each site is shown in parentheses):

1. Vacherie dome, Louisiana (salt dome)
2. Cypress Creek dome, Mississippi (salt dome)
3. Richton dome, Mississippi (salt dome)
4. Yucca Mountain, Nevada (tuff)
5. Deaf Smith County, Texas (bedded salt)
6. Swisher County, Texas (bedded salt)
7. Davis Canyon, Utah (bedded salt)
8. Lavender Canyon, Utah (bedded salt)
9. Reference repository location, Hanford Site, Washington (basalt flows)

The location of these sites in their host States is shown in Figure 1-1.

The Act further requires the DOE to issue general guidelines to be used in determining the suitability of these potentially acceptable sites. In February 1983, the DOE published draft general guidelines for siting repositories (the guidelines). The DOE revised the guidelines after receiving extensive comments from the NRC, the States, Indian Tribes, other Federal agencies, and the public. The NRC concurred with the revised guidelines in June 1984, and the final guidelines were promulgated in December 1984 (DOE, 1984a).

The Act requires that, after the guidelines are issued, the DOE nominate at least five sites as suitable for site characterization. Section 112(b)(1)(E) of the Act requires that an environmental assessment be prepared for each site proposed for nomination as suitable for characterization. The contents of the environmental assessments are described in a later section of this chapter. The DOE must then recommend not fewer than three of those sites for characterization as candidate sites for the first repository.

During site characterization, the DOE will construct exploratory shafts for underground testing to determine whether geologic conditions will allow the construction of a repository that will safely isolate radioactive waste. The Act requires the DOE to prepare site-characterization plans for NRC review. After site characterization and an environmental impact statement are completed, the DOE will recommend one of the characterized sites for development as a repository.

Figure 1-1. Potentially acceptable sites for the first repository.

1.2 SUMMARY OF THE OVERALL SITING PROCESS

In seeking sites for geologic repositories, the DOE divides the siting process into the following phases: (1) screening, (2) site nomination, (3) site recommendation for characterization, (4) site characterization, and (5) site selection (recommendation for development as a repository). This section describes the site-screening process, which led to the identification of the nine potentially acceptable sites for the first repository listed in Section 1.1, and reviews how the process of site nomination and recommendation is implemented under the guidelines.

1.2.1 SITE SCREENING

During the screening phase, the DOE identified potential sites for characterization. This phase provides the information needed for judging which of these sites appear to justify the investment necessary to characterize them. Screening may consist of as many as four stages, each of which progressively narrows the study area to a smaller land unit. These stages are as follows:

1. A survey of <u>geologic provinces</u>, narrowing to <u>regions</u>. Regions are generally smaller than provinces but may extend across several States and occupy tens of thousands of square miles.

2. A survey of the <u>regions</u>, narrowing to <u>areas</u> that encompass hundreds to thousands of square miles. The regional screening phase was completed with the publication of regional characterization reports and area-recommendation reports.

3. A survey of the <u>areas</u>, narrowing to <u>locations</u> that usually occupy an area smaller than 100 square miles. This phase was completed with the publication of location-recommendation reports for bedded salt and site-recommendation reports for salt domes.

4. A survey of the <u>locations</u>, narrowing to <u>sites</u>, which are generally smaller than 10 square miles. While a location may be large enough to contain several sites, only one or two potential sites are usually identified in a particular location.

During each screening stage, the DOE identified as many potentially suitable land units as were judged to be necessary for an adequate sample to be studied in the next stage. Only the regions and areas believed most likely to contain suitable sites received further study; the evaluation of all others was deferred.

Data for comparing regions, areas, and locations became increasingly detailed as progressively smaller land units were considered and as exploration and testing were concentrated on them. National, province, and regional surveys were based on potential host rocks, published geologic maps, maps of earthquake epicenters, land use, available geohydrologic information, and other information available in the open literature. Area and location surveys require more thorough investigations, which included field exploration and testing and the drilling of boreholes to investigate subsurface hydrologic, stratigraphic, and geochemical conditions. The field studies were supported by laboratory studies that focused on both the waste-isolation and the engineering characteristics of potential host rocks.

The bedded-salt sites in Texas and Utah were identified through the general siting process described above, beginning with national surveys and progressively narrowing to locations and sites. The salt domes were selected by a screening that began with more than 200 domes and ended with the three sites identified as potentially acceptable.

Screening for sites in basalt and tuff was initiated when the DOE began to search for suitable repository sites on some Federal lands where radioactive materials were already present. This approach was recommended by the Comptroller General of the United States (1979). Although land use was the beginning basis for this screening of Federal lands, the subsequent progression to smaller land units was based primarily on evaluations of geologic and hydrologic suitability. The studies began at roughly the area stage.

The technical factors used to guide site-screening decisions have evolved throughout the site-search period and are specified in a number of published documents (Brunton and McClain, 1977; DOE, 1981; DOE, 1982a; International Atomic Energy Agency, 1977; NAS-NRC, 1978).

The sections that follow summarize how the DOE applied the screening process outlined above to determine that the nine sites listed in Section 1.1.2 are potentially acceptable. Section 2.2 of each environmental assessment discusses in detail how the DOE conducted site screening in specific geohydrologic settings.

1.2.2 SALT SITES

Salt was first recommended as a potentially suitable host rock for waste disposal in 1955, after the National Academy of Sciences-National Research Council evaluated many options (NAS-NRC, 1957). This recommendation was reaffirmed in subsequent reports (e.g., American Physical Society, 1978; NAS-NRC, 1970). Rock salt, which occurs both as bedded salt and in salt domes, has several characteristics that are favorable for isolating radioactive waste, including the following:

- Salt deposits that are sufficiently deep, thick, and laterally extensive to accommodate a repository are widespread in the United States and generally occur in areas of low seismic and tectonic activity.

- Many salt bodies have remained undisturbed and dry for tens of millions to several hundred million years.

- Because of its high thermal conductivity in comparison with other rock types, rock salt has the ability to efficiently dissipate the heat that will be generated by the waste.

- Salt deforms in a relatively plastic manner under high confining pressure so that fractures that might develop at repository depth would tend to close and seal themselves.

Screening of the entire United States in the 1960s and 1970s resulted in the identification of four large regions that are underlain by rock salt of sufficient depth and thickness to accommodate a repository and represent diverse geohydrologic conditions (Johnson and Gonzales, 1978; Pierce and Rich, 1962). The four regions are as follows:

- Bedded salt in the Michigan and Appalachian Basins of southern Michigan, northeastern Ohio, western Pennsylvania, and western New York (also called the "Salina Basin").
- Salt domes within a large part of the Gulf Coastal Plain in Texas, Louisiana, and Mississippi.
- Bedded salt in the Permian Basin of southwestern Kansas, western Oklahoma, northwestern Texas, and eastern New Mexico.
- Bedded salt in the Paradox Basin of southeastern Utah, southwestern Colorado, and northernmost Arizona and New Mexico.

This screening at the national level served as the basis for all subsequent screening in salt. After proceeding to the location phase, further screening of the Salina Basin salt deposits was deferred, and the last three regions were selected for further study.

1.2.2.1 Salt domes in the Gulf Coast salt-dome basin of Mississippi and Louisiana

There are more than 500 salt domes in the Gulf Coast salt-dome basin of Texas, Louisiana, Mississippi, and areas offshore from these States. An initial screening by the U.S. Geological Survey (USGS) eliminated all offshore domes. The application of this criterion eliminated about half the domes. The USGS also evaluated the remaining 263 onshore domes and identified 36 as being potentially acceptable for a repository and another 89 that were worthy of further study (Anderson et al., 1973). The USGS screening factors were depth to the top of the dome and present use for gas storage or hydrocarbon production.

The DOE and its predecessor agencies conducted regional studies of 125 salt domes identified in the earlier USGS screening mentioned above. All but 11 of the domes were eliminated on the basis of three screening factors: depth to salt, lateral extent of the domes, and potential for competing uses (NUS Corporation, 1978; ONWI, 1979). Three of the 11 domes were removed from consideration on the basis of environmental factors, and a fourth was eliminated because solution mining at the site contributed to a collapse of strata above the dome.

Area-characterization studies were completed for the seven remaining dome areas: Rayburn's and Vacherie domes in Louisiana; Cypress Creek, Lampton, and Richton domes in Mississippi; and Keechi and Oakwood domes in Texas. The geologic field work conducted during this phase included the drilling of deep holes to collect rock cores for laboratory tests of their properties, and geophysical surveys to determine the underlying rock structures. The area environmental studies included descriptions of the plant and animal communities, surface- and ground-water systems, weather conditions, land use, and socioeconomic characteristics. An evaluation of the seven domes on the basis of the DOE's criteria is summarized in a location-recommendation report (ONWI, 1982a).

In the area-characterization studies, a repository-size criterion was chosen that was more restrictive than the one used in earlier screening studies. The application of this stricter criterion resulted in the elimination of Keechi, Rayburn's, and Lampton domes (ONWI, 1982a). Thus, at the conclusion of area characterization, the Vacherie, Richton, Oakwood, and Cypress Creek domes were recommended for further screening. After further review of the area-characterization studies, the Oakwood dome was deferred from further consideration because of uncertainties raised by large-scale petroleum exploration.

In accordance with the Act, the DOE identified the Cypress Creek, Richton, and Vacherie domes as potentially acceptable sites in February 1983.

1.2.2.2 Bedded salt in the Paradox Basin

Screening criteria were developed for the bedded salt of the Paradox Basin, which the USGS had identified as worthy of further investigation (Pierce and Rich, 1962). The following factors were applied to identify areas for further investigation (Brunton and McClain, 1977; DOE, 1981; NUS Corporation, 1978): depth and thickness of salt, mapped faults, other evidence of recent geologic instability, zones of ground-water discharge, significant resources, and potential for flooding. The results of this screening were integrated with screening for environmental and socioeconomic factors, such as proximity to urban areas and the presence of certain dedicated lands. On the basis of this regional screening, four areas were recommended for further study: Gibson Dome, Elk Ridge, Lisbon Valley, and Salt Valley (ONWI, 1982b).

The screening factors used to identify potentially favorable locations within the four areas were the depth to salt, the thickness of salt, proximity to faults and boreholes, and proximity to the boundaries of dedicated lands (ONWI, 1982c). These screening factors were judged to have the strongest potential for differentiating possible locations within the areas.

Salt Valley and Lisbon Valley were both deferred from further consideration because all areas with an adequate depth to salt were too close to zones of mapped surface faults and, for Lisbon Valley, because of existing boreholes (ONWI, 1982c).

Application of the screening factors to the Gibson Dome showed a location of 57 square miles near the center of the area that contained appropriately deep and thick salt deposits and was sufficiently far from faults or exploration boreholes that would make a site unsuitable. It also appeared to be sufficiently distant from dedicated lands. This location is referred to as the Gibson Dome location. The Elk Ridge area contained one location of about 6 square miles and several smaller ones, each less than 3 square miles, that met the screening criteria (ONWI, 1982c). The smaller locations were not large enough for a repository and were therefore excluded from further consideration. The larger location was designated the Elk Ridge location.

Further comparisons of the Gibson Dome and Elk Ridge locations were made on the basis of more-refined criteria that discriminated between them. The thickness of salt, the thickness of shale above and below the depth of a repository, and the minimum distance to salt-dissolution features were considered the most critical geologic discriminators. Archaeological sensitivity and site accessibility were considered the most important environmental factors. The Gibson Dome location was judged to be superior to the Elk Ridge location in terms of the number and relative importance of favorable factors and was selected as the preferred location (ONWI, 1982c).

During 1982 and 1983 three sites were identified for further evaluation: Davis Canyon, Lavender Canyon, and Harts Draw. Since much of the intrinsic value of southeastern Utah stems from its scenic and aesthetic character, a study of visual aesthetics was performed to evaluate the three sites (Bechtel Group Inc., 1983). Harts Draw was found to be less desirable than the sites at Davis Canyon and Lavender Canyon because it affords a greater total area of visibility, and it was eliminated from further consideration. In February 1983, Davis Canyon and Lavender Canyon were identified as potentially acceptable sites.

1.2.2.3 Bedded salt in the Permian Basin

In 1976, the Permian bedded-salt deposits in the Texas Panhandle and western Oklahoma that were identified in the USGS study (Pierce and Rich, 1962) were evaluated to determine whether they contained any areas that might be suitable for waste disposal (Johnson, 1976). Since the parts of the Permian Basin in western Kansas and Texas and in eastern Colorado and New Mexico had been screened as part of an earlier site evaluation for the Waste Isolation Pilot Plant (WIPP), this screening focused on five subbasins: the Anadarko, Palo Duro, Dalhart, Midland, and Delaware Basins. All contain salt beds of adequate thickness and depth. A site had already previously been selected in the Delaware Basin as a site for the WIPP facility for radioactive defense wastes (DOE, 1980a). The Palo Duro and the Dalhart Basins had far less potential for oil and gas production and have not been penetrated as extensively by drilling as have the Anadarko and the Midland Basins. Therefore, the Palo Duro and the Dalhart Basins were judged to be preferable to the other three and were recommended for further studies at the area stage (ONWI, 1983a). These two basins rated higher on six major screening factors: the depth and thickness of salt, seismicity, known oil and gas deposits, the presence of exploratory boreholes, and evidence of salt dissolution.

More-detailed geologic and environmental studies of the Palo Duro and the Dalhart Basins began in 1977, and screening criteria were developed to define locations with favorable characteristics. Six locations in parts of Deaf Smith, Swisher, Oldham, Briscoe, Armstrong, Randall, and Potter Counties, Texas, met the screening criteria. A second set of criteria was then applied to further differentiate among the six locations. These criteria reflected siting factors related to geomorphology, the presence of natural resources, flexibility in repository siting at specific locations, the number of boreholes at each location, population density, and land-use conflicts. After applying these criteria, the DOE decided to focus on the two locations that had the greatest likelihood of containing a suitable site, one in northeastern Deaf Smith and southeastern Oldham Counties and one in northcentral Swisher County. All other locations in the Palo Duro Basin were deferred from further consideration (ONWI, 1983b). In February 1983, the DOE identified parts of Deaf Smith County and Swisher County as potentially acceptable sites and subsequently narrowed the size of the two sites to be considered at each location (DOE, 1984b).

1.2.3 SITES IN BASALT AND TUFF

In 1977, the waste-disposal program was expanded to consider previous land use as an alternative basis for site screening. This approach considered the advantages of locating a repository on land already withdrawn and committed to long-term institutional control. Because both the Hanford Site and the Nevada Test Site are dedicated to nuclear operations, will remain under Federal control, and are underlain by potentially suitable rocks, screening was initiated in these two areas.

1.2.3.1 Basalt in the Pasco Basin, Washington

The DOE and its predecessor agencies have investigated the geologic and hydrologic characteristics of the Pasco Basin since 1977 as a continuation of studies conducted for the defense-waste-management program between 1968 and 1972 (Gephart et al., 1979; Myers et al., 1979). These investigations showed that the thick formations of basalt lava in the Pasco Basin are suitable for further investigation as a geologic repository for the following reasons:

- Several basalt flows more than 2100 feet below ground apparently are thick enough to accommodate a geologic repository.

- The slow rate of deformation of the basalt ensures the long-term integrity of a repository at the Hanford Site. Also, there are synclines where structural deformation appears to be limited.

- The potential for renewed volcanism at the Hanford Site is very low.

- The likely geochemical reactions between the basalt rock, ground water, and the waste are favorable for long-term isolation.

The Pasco Basin was selected for screening to provide a broader scope from which to study processes that might affect the Hanford Site and to determine whether there are any obviously superior sites in the natural region outside, but contiguous with, the Hanford Site (Woodward-Clyde Consultants, 1980, 1981).

The first step in screening was to define the candidate area. The considerations used at this step were fault rupture, ground motion, aircraft traffic, ground transportation, operational radiation releases from nuclear facilities at the Hanford Site, protected ecological areas, culturally important areas, and site-preparation costs. A candidate area was identified that included the central part of the Hanford Site and adjacent land east of the Hanford Site.

The second step in the screening was to define subareas (locations). The siting factors used in this screening step were fault rupture, flooding, ground failure, erosion, the presence of hazardous facilities, induced seismicity, and site-preparation costs. This step eliminated approximately half the candidate area.

Locations were identified through an evaluation of the subareas inside and adjacent to the Hanford Site. On the basis of land use, hydrologic conditions, and bedrock dip, subareas outside the Hanford Site were eliminated because they were not obviously superior to those found within the Hanford Site. After eliminating these subareas, five locations were identified within the boundaries of the Hanford Site.

The identification of candidate sites from among the five locations was based on an evaluation of 23 parameters (Rockwell 1980, 1981). Nine candidate sites were identified, seven of which lay in the Cold Creek Syncline, a major structural feature of the Pasco Basin. This syncline was selected partly because it is not as extensively deformed as nearby anticlines and is underlain by relatively horizontal strata. Since the other two sites were not technically superior to those in the Cold Creek Syncline and were closer to the Columbia River, they were removed from further study. To avoid some geophysical anomalies of uncertain source, three other sites were identified; they were largely superimposed on parts of the original seven sites in the Cold Creek Syncline (Myers and Price, 1981).

Since preliminary evaluations of the resulting 10 partly overlapping candidate sites indicated that the sites were too closely matched to be differentiated by routine ranking, a formal decision analysis was used to identify the best site (Rockwell, 1980). Decision criteria were derived from the following siting factors: bedrock fractures and faults, lineaments, potential earthquake sources, ground-water-travel times, contaminated soil, surface facilities, thickness of the proposed repository horizon, repetitive occurrence of columnar-jointed zones (colonnades) within the host flow, natural vegetative communities, unique microhabitats, and special species. The analysis showed that two approximately coincident sites rated higher than the other sites. These two sites were combined and designated "the reference repository location." In February 1983, the DOE identified the reference repository location as a potentially acceptable site.

1.2.3.2 Tuff in the Southern Great Basin, Nevada

At the same time that the DOE was considering the Nevada Test Site (NTS) on the basis of land use, the USGS proposed that the NTS be considered for investigation as a potential repository site for a variety of geotechnical reasons, including the following:

- Southern Nevada is characterized by closed hydrologic basins. This means that ground water does not discharge into rivers that flow to major bodies of surface water.

- Long flow paths occur between potential repository locations and ground-water discharge points.

- Many of the rocks occurring at the NTS have geochemical characteristics that are favorable for waste isolation.

- The NTS is located in an arid region (6 to 8 inches per year of rainfall). With the very low rate of recharge, the amount of moving ground water is also low, especially in the unsaturated zone.

In 1977, the geologic medium of prime interest at the NTS was argillite (a clay-rich rock), which occurs under the Syncline Ridge, near the center of the NTS. Geologic investigations and exploratory drilling there revealed a complex geologic structure in the center of the area being considered (Hoover and Morrison, 1980; Ponce and Hanna, 1982). It was decided in July 1978 that the geologic complexity of the area would make characterization prohibitively difficult, and further evaluation was deferred.

A question then arose concerning the compatibility of a repository with the testing of nuclear weapons—the primary purpose of the NTS. A task group formed to evaluate this issue determined in 1978 that a repository located in other than the southwestern portion of the NTS might be incompatible with weapons testing. At that time the program refocused on the area in and around the southwestern corner of the NTS, which subsequently was named the Nevada Research and Development Area (NRDA). The entire area then being evaluated included land controlled by the Bureau of Land Management west and south of the NRDA and a portion of the Nellis Air Force Range west of the NRDA.

In August 1978, a preliminary list of potential sites in and near the southwestern part of the NTS was compiled. The areas initially considered included Calico Hills, Skull Mountain, Wahmonie, Yucca Mountain, and Jackass Flats. Of these five areas, Calico Hills, Wahmonie, and Yucca Mountain were considered the most attractive locations for preliminary borings and geophysical testing.

The Calico Hills location was known to contain argillite. It was of particular interest because a geophysical survey showed that granite might occur approximately 1600 feet below the surface. The first exploratory hole for waste-disposal studies at the NRDA was drilled in 1978 in an attempt to confirm the existence of granite beneath the Calico Hills. Drilling was discontinued at a depth of 3000 feet without reaching granite (Maldonado et al., 1979). Additional geophysical surveys indicated that the argillite at Calico Hills is probably very complex structurally, comparable with that at Syncline Ridge (Hoover et al., 1982). Because the granite was considered too deep and the argillite appeared too complex, further consideration of the Calico Hills was suspended in the spring of 1979.

Concurrent with drilling at Calico Hills, geophysical studies and surface mapping conducted at Wahmonie indicated that the granite there may not be large enough for a repository, that any granite within reasonable depths may contain deposits of precious metals, and that faults in the rock may allow vertical movement of ground water (Hoover et al., 1982; Smith et al., 1981). For these reasons, Wahmonie was eliminated from consideration in the spring of 1979.

Surface mapping of Yucca Mountain indicated the existence of a generally undisturbed structural block large enough for a repository. In 1978, the first exploratory hole drilled at Yucca Mountain confirmed the presence of thick, highly sorptive units of tuff (Spengler et al., 1979). Because tuff previously had not been considered as a potential host rock for a repository, a presentation was made to the National Academy of Sciences (NAS) Committee for Radioactive Waste Management in September 1978 to solicit its views on the potential advantages and disadvantages of tuff as a repository host rock. The NAS committee supported the concept of investigating tuff as a potential host rock (DOE, 1980b), and in a letter dated February 5, 1982, to the DOE Nevada Operations Office, the USGS pointed out the considerable advantages of locating a repository in the unsaturated zone. After comparing the results of preliminary exploration at Calico Hills, Wahmonie, and Yucca Mountain, the USGS recommended that attention be focused on Yucca Mountain. A technical peer-review group supported the DOE's decision to concentrate exploration efforts on the tuffs of Yucca Mountain (DOE, 1980b).

Because the foregoing process of selecting Yucca Mountain for early exploration was not highly structured, a more thorough, formal analysis was begun in 1980 to evaluate whether Yucca Mountain was indeed appropriate for further exploration. This analysis was conducted in a manner compatible with the area-to-location phase of site screening described in the national siting plan (DOE, 1982b), which was used by the DOE before the passage of the Act and the formulation of the guidelines. Details of the formal analysis are presented by Sinnock and Fernandez (1984). In brief, this formal decision analysis evaluated 15 potential locations and concluded that Yucca Mountain was indeed the preferred location. Several potentially suitable horizons were identified in the saturated and unsaturated zones. Therefore, the DOE identified Yucca Mountain as a potentially acceptable site in February 1983.

1.2.4 NOMINATION AND RECOMMENDATION OF SITES FOR CHARACTERIZATION

The preceding sections described the siting process from its beginning to the point where nine sites had been identified as being potentially acceptable. The next steps are mandated by the Act: the Secretary of Energy is to nominate at least five sites that are suitable for characterization and to recommend to the President not fewer than three of those sites for characterization as candidate sites for the first repository. The discussion that follows assumes some knowledge of the form and content of the DOE's siting guidelines. The reader unfamiliar with the guidelines is referred to Section 2.4 for a very brief description or to the guidelines themselves (DOE, 1984a) for a more detailed description.

The guidelines, in 10 CFR Part 960.3-2-2-2, require the DOE to implement the following six-part process in selecting sites for nomination as suitable for characterization from among the potentially acceptable sites:

1. Evaluate the potentially acceptable sites in terms of the disqualifying conditions specified in the guidelines.

2. Group all potentially acceptable sites according to their geohydrologic settings.

3. For the geohydrologic settings that contain more than one potentially acceptable site, select the preferred site on the basis of a comparative evaluation of all potentially acceptable sites in that setting.

4. Evaluate each preferred site within a geohydrologic setting and decide whether such site is suitable for the development of a repository under the qualifying condition of each guideline that does not require site characterization as a prerequisite for such evaluation.

5. Evaluate each preferred site within a geohydrologic setting and decide whether such site is suitable for site characterization under the qualifying condition of each guideline that requires characterization for evaluation of suitability for development as a repository.

6. Perform a reasonable comparative evaluation under each guideline of the sites proposed for nomination.

To document the process specified above, draft environmental assessments (EAs) were prepared for each of the nine sites identified as potentially acceptable (DOE, 1984c-g). The draft EAs, which also include the evaluations and descriptions specified by the Act, were issued for public comment in December 1984. The draft EAs proposed the following five sites (listed together with their corresponding geohydrologic setting) for nomination:

Geohydrologic setting	Site
Columbia Plateau	Reference repository location at the Hanford Site, Washington
Great Basin	Yucca Mountain, Nevada
Permian Basin	Deaf Smith County, Texas
Paradox Basin	Davis Canyon, Utah
Gulf Coastal Plain	Richton Dome, Mississippi

In addition to requesting written comments on the draft EAs, the DOE held a series of public briefings and hearings to receive oral comments. More than 20,000 comments were received, and among them were many comments on the three simple ranking methodologies presented in Chapter 7 of the draft EAs. The decisions to adopt a formal decision-analysis methodology and to prepare this separate report were made largely in response to the comments on the draft EAs. Also in response to public comments, the DOE requested that the Board on Radioactive Waste Management of the National Academy of Sciences conduct an independent review of the methodology.

On consideration of all of the comments on the draft EAs and the available evidence, evaluations, and resultant findings in the now final EAs (DOE, 1986a-e), the Secretary has determined that the five sites proposed for nomination in the draft EAs should be formally nominated. A notice specifying the sites so nominated and announcing the availability of the final EAs has been published in the Federal Register.

The screening and nomination processes have served the purpose of focusing closer scrutiny and more-rigorous evaluation on successively smaller areas. This progression to smaller land units was based primarily on evaluations of geologic and hydrologic suitability. With the completion of each step there has been greater basis for confidence that the remaining sites are technically sound. Thus, the selection of three sites to recommend for characterization is being made from among a set of five sites that have been nominated for consideration only after passing many increasingly stringent tests.

The site-recommendation decision must be based on the available geophysical, geologic, geochemical, and hydrologic data; other information; the evaluations and findings reported in the environmental assessments accompanying the nominations; and the diversity considerations specified below. The siting guidelines (10 CFR 960.3-2-3) specify that these data are to be applied in two distinct steps:

1. Determination of an initial order of preference for sites for characterization.

2. Determination of a final order of preference for sites for characterization, based on diversity of geohydrologic settings and diversity of rock types.

The formal analysis of sites presented herein is being used to determine the initial order of preference for sites for recommendation for characterization.

In determining a final order of preference of sites, the siting guidelines specify that, to the extent practicable, consideration be given to diversity of geohydrologic settings and of rock types. The diversity considerations arise from the premise that sites located in the same geohydrologic setting or in the same rock type may be subject to a common flaw. Also, because diverse geohydrologic settings imply differences in the nature of the accessible environment (e.g., a setting with surface-water bodies versus a desert environment), it is possible to consider whether the same quantity of radionuclides released from a repository at different sites might lead to drastically different consequences over the long term after repository closure (see Chapter 3).

The purpose of the process outlined above is to ensure that the sites recommended as candidate sites for characterization offer, on balance, the most advantageous combination of characteristics and conditions for the successful development of a repository at those sites.

1.3 ORGANIZATION OF THE REPORT

The remainder of this report (Chapters 2 through 5) presents the formal analysis of the comparative advantages and disadvantages of the five sites nominated as suitable for site characterization. Chapter 2 presents an overview of the formal decision-analysis technique known as multiattribute utility analysis. The role of the methodology and the process of its application are explained, its relationship to the DOE siting guidelines is discussed, and the basic steps in the methodology are outlined.

Chapters 3 and 4 present in summary form the postclosure and the preclosure analyses, respectively, of the five nominated sites. These analyses are based on the formal decision-aiding methodology. Results are presented for both a base case and for numerous sensitivity analyses.

Chapter 5 presents the composite analysis of the results presented in the two preceding chapters. These overall results form the basis for determining an initial order of preference for sites for characterization.

There are eight appendixes. Appendix A identifies the participants in the development and application of the the decision-aiding methodology. Appendixes B, C, and D contain detailed information on the postclosure analysis summarized in Chapter 3. Appendixes E and F contain detailed information on the preclosure analysis summarized in Chapter 4.

Appendix G presents background information on the multiattribute utility theory and detailed information on the assessed value tradeoffs and various other assumptions made in the application of the methodology.

Finally, Appendix H discusses the DOE's interactions with the Board on Radioactive Waste Management of the National Academy of Sciences on the development and application of the decision-aiding methodology. It also reproduces most of the DOE's correspondence with the Board.

For the convenience of the reader a glossary of terms is included.

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Chapter 2

THE DECISION-AIDING METHODOLOGY: OVERVIEW AND RELATIONSHIP TO THE SITING GUIDELINES

2.1 BACKGROUND AND INTRODUCTION

After selecting five sites for nomination as suitable for characterization, the DOE developed and applied a formal decision-analysis methodology as an aid in deciding which sites are preferred for recommendation for characterization. The methodology, which is based on multiattribute utility theory, involves an analysis that explicitly weighs the pros and cons of the nominated sites. Such an analysis can be a significant aid to decisionmakers; it can also help to objectively communicate the basis for the decision. Specifically, such an analysis can assist decisionmakers in three ways. It can--

- Provide information needed for judging which sites appear to justify the investment in characterizing them.

- Add credibility to the decision process.

- Provide a mechanism to facilitate constructive discussion and mediate potential conflict.

To achieve these goals the analysis should provide insights to help the decisionmakers understand which sites are more desirable than others and why. Furthermore, the analysis should illuminate which factors (e.g., data, professional judgments, value judgments, models) seem to be most crucial to the relative desirability of the sites. These suggest the sensitive issues to which more-careful analyses and time should be devoted. The decision process acquires credibility from the use of a sound logic and reasonable data, judgments and assumptions to provide understandable conclusions. By providing a model of the key factors in the decision problem, the analysis can be easily repeated to incorporate other viewpoints, and the implications of the differences can be easily identified and examined, thus facilitating discussion and the resolution of potential conflicts.

As mentioned, the analysis of the nominated sites is based on multiattribute utility theory. It has been applied to numerous other siting problems, such as power plants, dams, and refineries (see Keeney, 1980, for additional examples). The logical foundations of multiattribute utility analysis and the systematic procedures for its implementation have been well documented in the professional literature over the past 40 years (see, for example, von Neumann and Morgenstern, 1947; Savage, 1954; Pratt, Raiffa, and Schlaifer, 1964; Fishburn, 1970; and Keeney and Raiffa, 1976). The analysis also relies on the professional experience, judgment, data, and models that have been developed in the numerous disciplines involved in repository siting and in particular the evaluations of each nominated site against the siting guidelines (DOE, 1984), as reported in the environmental assessments that accompanied the nomination (DOE, 1986a-e).

The selection of multiattribute-utility theory for analyzing the site-recommendation problem is based on three advantages of the theory. First, it has an explicitly stated philosophical and logical basis for the methodology that is appropriate for the site-recommendation problem (see Merkhofer, 1986). Second, it separates the factual information and judgments about the performance and impacts of a repository at the various sites from value judgments about the desirability of those possible impacts. And third, both of these sets of information and judgments are made explicit for peer review and public review.

Crucial to multiattribute utility analysis are the sensitivity analyses that are conducted. The sensitivity analyses vary over reasonable ranges any of the inputs that could substantially affect the relative desirability, and hence the initial order of preference, of the nominated sites. Their purpose is to ascertain whether specific judgments or data are crucial to the conclusions drawn from the analysis. They thus suggest where further attention and effort should be focused.

In spite of its advantages, a formal analysis cannot address every aspect of the complex siting decision faced here. Excluded from the analysis, for example, is consideration of the advantages of a diversity of rock types. Because this or any methodology is capable of providing only a partial accounting of the many factors important to the site-recommendation decision, its results will not form the sole basis for that decision.

Regarding the design of the methodology, one additional point should be made; it is related to the concept of the diversity of rock types. The method of analysis used here evaluates the overall desirability of each nominated site, not the desirability of combinations of sites. The evaluation of all possible combinations of sites, each of the possible combinations being considered as an alternative, would require an extended, more-difficult form of analysis known as a "portfolio analysis." As explained by Edwards and Newman (1982), such sophistication is rarely used in portfolio problems. Instead, the more-common procedure is to evaluate the options (i.e., sites) by methods similar to the one described here and then to examine the resulting set of choices to determine their acceptability as a portfolio. This is exactly the procedure outlined in Section 1.2.4.

The sections that follow present a brief overview of the methodology (Section 2.2), explain the process by which it was implemented (Section 2.3), and discuss the relationship of the methodology to the DOE's siting guidelines (Section 2.4).

2.2 OVERVIEW OF THE ANALYSIS

The logic underlying multiattribute utility analysis is relatively straightforward, although the specific steps and the nomenclature may be unfamiliar to some readers. (A glossary is provided at the end of the report.) The basic premise is that the relative desirability of a site is measured by the extent to which siting objectives are achieved. The siting objectives are derived directly from the DOE's siting guidelines (see Section 2.4). The degree to which siting objectives are achieved is indicated by the performance and impacts predicted for a repository at the site. The performance and impacts are assessed on the basis of technical models, data, and professional judgment. The methodology is designed to aggregate these assessments in an appropriate and logical manner to provide an overall evaluation of the nominated sites.

The six basic steps of the methodology, as applied to the evaluation of sites, are the following:

1. Establish the objectives of repository siting and develop preclosure and postclosure performance measures for quantifying levels of performance with respect to these objectives.

2. For the postclosure analysis, specify a set of scenarios that, should they occur, might affect the performance of the repository system as represented by the postclosure-performance measures.

3. For each scenario, estimate postclosure performance with respect to each postclosure-performance measure. Estimate preclosure performance and impacts with respect to each preclosure-performance measure.

4. Assess the relative values of different levels of performance against each objective (i.e., assess a utility function over each performance measure) and assess value tradeoffs to integrate the achievement of different objectives into an overall utility function.

5. Using the overall utility function, aggregate impacts to obtain a composite score indicating the relative desirability of each site.

6. Perform sensitivity analyses to determine which models, data, technical judgments, and value judgments seem most significant for drawing insights from the analysis.

Each of the steps is reviewed in more detail below.

Step 1: Establish Objectives and Develop Measures for Quantifying Levels of Performance

A basic premise of the decision-aiding methodology is that the "goodness," or the utility, of a site is related to the extent to which that site achieves the various objectives of a geologic repository for radioactive waste. Thus, the first step in the application of the methodology is to explicitly define objectives. It is convenient to organize the objectives in a tree, or hierarchical, structure, as shown in Figure 2-1.

The overall objective is to minimize the adverse impacts of a repository. This objective is divided into "minimize adverse preclosure impacts" and "minimize adverse postclosure impacts." Because such objectives are too broad to be of practical value in distinguishing among sites, more-detailed lower-level objectives necessary for meeting the top-level objectives were identified. These lower-level objectives make it easier to specify performance measures and describe site impacts. The lower-level objectives are shown in Figures 3-1 and 4-1 for the postclosure and the preclosure periods, respectively.

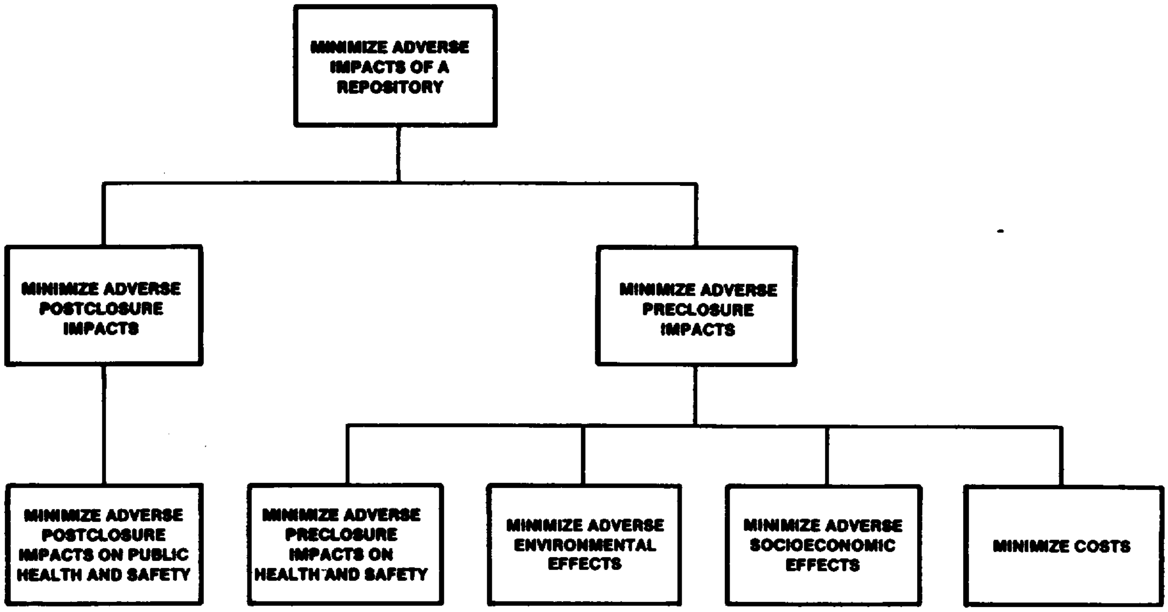

Figure 2-1. General objectives hierarchy for geologic disposal.

Any objectives hierarchy should capture collectively all of the important considerations relevant to a decision. The objectives hierarchy of Figure 2-1 (and Figures 3-1 and 4-1) is assumed to satisfy this goal because the objectives are derived from the DOE's system guidelines and technical guidelines (see Section 2.4), which were developed through an extensive process of consultation, public comment, and NRC concurrence. In developing an objectives hierarchy, care must be taken to avoid double-counting objectives. Extra or unnecessary objectives make the analysis more complex and reduce the quality of the insights provided.

After a hierarchy of objectives is developed, "yardsticks" must be devised to indicate how well a site meets them. Formally, these yardsticks are known as performance measures. The development of performance measures is a process that requires professional judgment, knowledge, and experience. Ideally, performance measures should be expressed in natural scales based on physical measurements or quantitative data. An example is the performance measure of millions of dollars for the objective "minimize costs." Inevitably, however, some measures concern intangible impacts that are not easily described or quantified. For these cases a performance measure must be constructed, as illustrated by the example in Table 2-1. The ranges spanned by any performance measure should be realistic in order to describe the impacts of all sites being evaluated.

In this particular application of the multiattribute utility analysis, a graphic device known as an influence diagram was constructed for each performance measure. The influence diagrams, shown for all performance measures in Appendixes B and E, indicate the factors that must be accounted for in describing the possible site impacts and the interrelationships among these factors. An example of an influence diagram is shown later in the chapter (Figure 2-2). Many of the factors in the influence diagrams may be derived directly from the statements of the disqualifying, favorable, or potentially adverse conditions in the siting guidelines.

Step 2: Specify Scenarios That, if They Occur, Might Affect Postclosure Performance

A good repository site should perform well under nominal, or expected conditions. It should also perform well even if the site contains unexpected features or if disruptive events and processes occur. To estimate and account for risks, it is necessary to identify the disruptions that may adversely affect each site and to estimate the performance of the repository under these conditions.

To account for the risks of unexpected features and disruptive events or processes, scenarios are used in the postclosure analysis of sites. (As explained in Appendix F, preclosure accident scenarios are not considered because they are not expected to be significant site discriminators.) Scenarios are postulated conditions or sequences of processes or events that could affect the postclosure performance of a repository. Each scenario may be regarded as a possible "future" for a repository over a 10,000-year of the period. Examples of scenarios would be exploratory drilling within the controlled area around a repository and movement of a large fault in the repository.

Table 2-1. Example of constructed performance measure for the objective "minimize biological impacts" for a specific problem context[a]

Score	Description
0	No loss of productive wetland and no members of rare species present
1	Loss of 320 acres of productive wetland and no members of rare species present
2	Loss of 640 acres of productive wetland and no members of rare species present or 30 members of rare species present and no productive wetland loss
3	No loss of productive wetland and 50 members of rare species present
4	Loss of 640 acres of productive wetland and 40 members of rare species present
5	Loss of 640 acres of productive wetland and 50 members of rare species present

[a]Modified after R. L. Keeney, Siting Energy Facilities, Academic Press, New York, 1980.

For a scenario to be considered for a site, it must satisfy two conditions. First, it must be reasonably likely to occur. Sequences of events or processes that are impossible or so unlikely as to not merit serious attention are not considered. Second, a scenario must have a chance of producing a significant change in repository performance. For example, the score achieved by a site should change from the nominal case by at least one unit if the scenario occurs.

Scenarios for each site were developed by a panel of individuals selected for their expertise in the processes and events that might alter repository performance. Lists of scenarios were screened to find those with some likelihood of occurrence and a potential for affecting performance. Scenarios were designed to be nonoverlapping (so that the occurrence of any one would preclude the occurrence of any other) and exhaustive (so that one and only one scenario could be presumed to occur). The panel provided judgmental estimates of the probability of each scenario's occurring at each site. Since panel members differed slightly in their estimates, high- and low-probability estimates were provided in addition to base-case estimates.

Step 3: Score Each Site on Each Measure and for Each Scenario

The next step in the methodology is to assess each site, using the performance measures developed in step 1 and the scenarios developed in step 2. For the preclosure analysis, such assessments result in a base-case estimate and a range for the possible impacts of each site indicated in terms of the performance measures. These estimates are based on technical models, data, and professional experience. For the postclosure analysis, base-case estimates and a range are provided for the nominal-case scenario and for each of the disruptive scenarios that apply to that site. These estimates are based on technical analyses and professional judgments.

Step 4: Assess the Multiattribute Utility Function

To account for differences in the importance of different impacts, it is necessary to assess values for different impact levels, and these values must be used to arrive at a common scale of desirability. Such a scale is referred to as a "utility scale," and the transformation from impacts to utility is provided by a multiattribute utility function for both preclosure and postclosure performance. For the preclosure analysis, a scale of 0 to 100 was adopted, with 0 assigned to the highest and 100 assigned to the lowest of possible impact levels. For the postclosure analysis, 100 was also assigned to the lowest possible impact level, but the possibility of a negative utility was also included in the scale. On the postclosure scale, a 0 represents just meeting applicable regulatory requirements. The desirability of any site can be indicated by its utility by substituting the impact levels into the multiattribute utility function. Higher utilities imply preferred consequences (i.e., sets of impacts). In cases of uncertainty, the mathematical expected utility, obtained by multiplying the probabilities of consequences by the utilities of these consequences, is the appropriate indicator of site desirability (see von Neumann and Morgenstern, 1947).

The multiattribute utility function assessed for this analysis is presented in Appendix G. As discussed in detail in this appendix, it is constructed from responses to many detailed questions about value judgments appropriate for the site evaluations. Because such value judgments are largely policy, rather than technical, judgments, they were elicited from DOE management.

Step 5: Aggregate Impacts and Values To Provide an Overall Evaluation of Nominated Sites

At this point in the methodology, four sets of information are available: (1) probabilities for each postclosure scenario for each site, (2) a collection of postclosure-impact estimates for each postclosure scenario at each site, (3) a collection of preclosure-impact estimates for each site, and (4) the multiattribute utility function. These sets of information are aggregated into a composite evaluation of sites in three steps.

In the first step, for each site and postclosure scenario, the utility is calculated for each consequence. This is multiplied by the corresponding scenario-probability estimate, and the results are summed to obtain the expected postclosure utilities for each site. These expected utilities indicate the relative postclosure desirability of each site. Sensitivity analyses were used to examine the implications of uncertainties in the postclosure analysis.

In the second step, the utility of each consequence representing preclosure site impacts is determined by using the preclosure utility function. These utilities indicate the relative preclosure desirability of each site. Sensitivity analyses were also used to examine the implications of uncertainties in the preclosure analysis.

The third step is to combine the various expected postclosure and preclosure utilities into an overall composite utility for each site. This is accomplished by multiplying both preclosure and postclosure utilities by weights obtained from assessed value judgments about the relative importance of postclosure and preclosure impacts.

The most difficult of the value judgments concern value tradeoffs, which may involve impacts of a similar nature (e.g., costs of one type versus costs of another type, different types of environmental impacts, and different health-and-safety impacts) or impacts of a different nature (e.g., health effects versus costs). The value tradeoffs among impacts of a similar nature may be easier to make and to clarify and justify than the value tradeoffs between impacts of different types. To specify the value tradeoffs between health effects and costs or between costs and environmental as well as socioeconomic impacts is not an easy task. And yet it may be that these value tradeoffs are crucial to establishing the relative desirability of the nominated sites. Because of this possibility, they should be explicitly considered in the analysis. The value judgments assessed for this purpose are presented in Appendix G.

Step 6: Perform Sensitivity Analyses

The purpose of sensitivity analyses is to test how the overall utilities calculated in step 5 change as assumptions and judgments change. If the implications from the original analysis are resilient under changes in assumptions and judgments, they are more likely to be valid. An obvious sensitivity analysis is to vary the value judgments, since different people have different opinions on the relative importance of various siting impacts. Other input data for the methodology, such as the site impacts (step 3), should also be varied.

Summary

One of the major assets of the decision-aiding methodology is that it divides the problem of selecting sites for characterization into several parts that can be analyzed and scrutinized more easily. The methodology does not reduce the professional judgment required in selecting sites for characterization. By following the sequence of steps outlined above, however, the DOE hopes to make these scientific and policy judgments explicit to the reviewer. The methodology does this in essentially five ways. First, it specifies and organizes the DOE's siting objectives. Second, it provides a means for summarizing how well each site meets each objective. Third, it provides a means for specifying alternative value judgments about the relative importance of impacts with respect to each objective. Fourth, it provides a systematic way to aggregate site impacts on individual objectives. Finally, the methodology allows the DOE to test how implications change as judgments and assumptions change.

2.3 APPLICATION PROCESS AND PARTICIPANTS

Having identified and described the steps in the methodology, it is worthwhile to discuss briefly the process and participants involved in conducting the steps in the methodology. Additional details on the application process are given in Chapters 3 and 4. The participants and their qualifications are listed in Appendix A.

A task force for developing and carrying out the methodology was established within the DOE's Office of Civilian Radioactive Waste Management (OCRWM), and a management plan for this purpose was developed. The task force was composed of three separate groups. One group, consisting of DOE staff and experts in decision analysis and other disciplines, was responsible for seeing that the methodology was carried out according to the procedures and sequence of application recommended in the professional literature. This group was under the general oversight of the senior DOE managers (see below). The other two groups provided the two major inputs required for the methodology: technical judgments and value judgments.

To provide the technical judgments, six panels of technical specialists were established. Each panel was responsible for a major technical area represented in the siting guidelines, and the responsibilities of the panels are consistent with functional responsibilities and staff responsibilities for program execution within the OCRWM. Specifically, panels were established to evaluate all sites in the following areas:

- Postclosure repository performance.
- Preclosure radiological safety.
- Environment.
- Socioeconomics.
- Transportation.
- Ease and cost of siting, construction, operation, and closure.

The technical specialists were thoroughly familiar with the information (i.e., data, models, etc.) contained in all five environmental assessments (DOE, 1986a-e) and with the siting guidelines. They developed the measures for quantifying levels of performance, the scenarios and probabilities required to assess postclosure repository performance, and the estimates of the performance (i.e., scores) of each site on each performance measure. A decision analyst assisted in the process of constructing the performance measures and scenarios and formally elicited the probability of each postclosure scenario for each site. The decision analysts were less involved in the estimation of performance, since this is mainly the purview of the technical specialists.

The technical knowledge and experience of the individuals participating on each panel varied, depending on the responsibilities of the panel (e.g., assessments of postclosure repository performance are highly multidisciplinary, requiring experts in geology, hydrology, geochemistry, performance assessment, nuclear physics, etc.). All technical specialist panels consisted of a lead person from DOE headquarters and technical support staff. None of the three DOE Operations Offices that are involved in the repository program or their prime contractors participated in the scoring of the sites.

The aspects of the methodology that deal with preferences--that is, value judgments--were assigned to DOE management. In particular, four senior DOE managers in the Office of Civilian Radioactive Waste Management participated in the specification of the siting objectives, the verification of independence assumptions required to define the multiattribute utility function, and the specification of utility curves and value tradeoffs among objectives. The decision analysts formally elicited these value judgments. Care was taken to maintain separation between technical and value judgments. Thus, the DOE managers had no knowledge of the formal estimates of site impacts, and the technical specialists had no knowledge of the value tradeoffs among impacts before their aggregation into the composite evaluation of the sites reported here.

2.4 RELATIONSHIP BETWEEN THE ANALYSIS AND THE SITING GUIDELINES

The decision-aiding methodology must be consistent with the DOE siting guidelines, 10 CFR Part 960 (DOE, 1984). This consistency can be explained most easily after briefly reviewing the structure of the guidelines.

The siting guidelines are organized into three categories: implementation (see below), postclosure guidelines, and preclosure guidelines. The postclosure guidelines deal with the siting considerations that are most important for ensuring long-term protection (10,000 years) for the health and safety of the public. The preclosure guidelines deal with the siting considerations important to the operation of a repository before it is closed (about 80 years), such as protecting the public and repository workers from exposures to radiation, protecting the quality of the environment, mitigating adverse socioeconomic impacts, and the ease and cost of repository construction and operation. Both the postclosure and the preclosure guidelines are divided into system and technical guidelines. System guidelines contain broad repository-performance requirements that are largely derived from applicable regulations promulgated by the U.S. Environmental Protection Agency (EPA) and the U.S. Nuclear Regulatory Commission (NRC). The technical guidelines specify requirements on one or more elements of the repository system. Each guideline (system and technical) contains a qualifying condition. Taken together, these qualifying conditions are the minimum conditions for site qualification. Twelve technical guidelines also contain disqualifying conditions, which describe a condition so adverse as to constitute sufficient evidence to conclude, without further consideration, that a site is disqualified. Both the postclosure and the preclosure technical guidelines specify conditions that would be considered favorable or potentially adverse.

As explained in Section 2.2, a basic premise of the decision-aiding methodology is that the overall desirability of a site is related to the extent to which the site achieves the various objectives of site selection. The identification of objectives is a very important task in any siting problem. This task was simplified here because the objectives are readily derived from the siting guidelines, especially from the system guidelines.

At a broad level, the DOE believes that it is important to ensure that the fundamental concerns of the guidelines have been reflected in the methodology. Toward this end Table 2-2 has been prepared as a guidelines-to-objectives index. As can be seen, all guidelines* can be traced to one or more objectives. In fact, some guidelines--for example, the technical guideline on transportation--correspond to more than one objective defined for use in the methodology. Besides the statements of the guidelines themselves, the interested reader is referred to the "Supplementary Information" and Appendix IV of the guidelines (DOE, 1984) for evidence of the correspondence between the guidelines and the objectives.

With regard to the favorable and potentially adverse conditions, these conditions are intended to provide preliminary indications of system performance and are intended to be used in the screening phase of site selection, during the search for potentially acceptable sites. Notwithstanding, these conditions are useful at this stage of the siting process as well. Many of the conditions served to guide the specification of the factors in the influence diagrams shown in Appendixes B and E. The influence diagrams, in turn, were used in the scoring process.

As an illustration of the relationship between favorable and potentially adverse conditions and the decision-aiding methodology consider Figure 2-2, which shows a portion of the influence diagram for the postclosure analysis.

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*No attempt was made to include explicitly the disqualifying conditions of the technical guidelines. As explained in detail in Chapters 2 and 6 of each environmental assessment (DOE, 1986a-e), the evidence does not support a finding that any of the sites is disqualified. In addition, it is often the case that the concerns of the disqualifying conditions are represented in the performance measures defined for use in the methodology. For example, the ground-water travel time, the key factor in the disqualifying condition in the guideline on geohydrology, is included in the postclosure performance measures.

Table 2-2. Index showing correspondence between the qualifying conditions of the siting guidelines and siting objectives

Section 960	Guideline	Related siting objective(s)[a]
4-1(a)	System guideline on postclosure performance	
4-2-1(a)	Geohydrology	
4-2-2(a)	Geochemistry	
4-2-3(a)	Rock characteristics	Radiological safety of the public for 0 to 10,000 and 10,000 to 100,000 years after closure
4-2-4(a)	Climatic changes	
4-2-5(a)	Erosion	
4-2-6(a)	Dissolution	
4-2-(a)	Tectonics	
4-2-8-1(a)	Natural resources	
4-2-8-2(a)	Site ownership and control	
5-1-(a)(1)	System guideline on pre-closure radiological safety	Radiological safety, public, repository; radiological safety, workers, repository; radiological safety, public, transportation; radiological safety, workers, transportation
5-1(a)(2)	System guideline on environment, socioeconomics, and transportation	Nonradiological safety, public, repository; nonradiological safety, public, transportation; aesthetic effects; biological effects; archaeological, cultural, and historical effects
5-1(a)(3)	System guideline on ease and cost of siting, construction, operation, and closure	Nonradiological safety, workers, repository; nonradiological safety, workers, transportation; total repository costs; total transportation costs
5-2-1(a)	Population density and distribution	Radiological safety, public, repository
5-2-2(a)	Site ownership and control	Radiological safety, public, repository
5-2-3(a)	Meteorology	Radiological safety, public, repository; nonradiological safety, workers, repository; total transportation costs
5-2-4(a)	Offsite installations and operations	Radiological safety, public, repository; radiological safety, workers, repository; total repository costs
5-2-5(a)	Environmental quality	Nonradiological safety, public, repository; aesthetic effects; biological effects; archaeological, cultural, and historical effects
5-2-6(a)	Socioeconomic impacts	Socioeconomic effects

Table 2-2. Index showing correspondence between the qualifying conditions of the siting guidelines and siting objectives (continued)

Section 960	Guideline	Related siting objective(s)[a]
5-2-7(a)	Transportation	Radiological safety, public, transportation; radiological safety, workers, transportation; nonradiological safety, public, transportation; nonradiological safety, workers, transportation; total transportation costs
5-2-8(a)	Surface characteristics	Nonradiological safety, workers, repository; total repository costs
5-2-9(a)	Rock characteristics	Nonradiological safety, workers, repository; total repository costs; radiological safety, public, repository; radiological safety, workers, repository
5-2-10(a)	Hydrology	Nonradiological safety, workers, repository; total repository costs
5-2-11(a)	Tectonics	Nonradiological safety, workers, repository; total repository costs

[a]The objectives listed here are abbreviated versions of the objectives. The full statements of the objectives are given in Tables 3-1 and 4-1 for the postclosure and the preclosure periods, respectively.

The top half of the diagram contains a number of double ellipses, which indicate the most significant factors in the diagram. These factors can be readily associated with a number of favorable and (or) potentially adverse conditions specified for the technical guidelines on geohydrology, geochemistry, and rock characteristics. For example, the ground-water travel time (ellipse (26)) is a factor in favorable condition 1 and the criterion for the disqualifying condition for the guideline on geohydrology. (Ground-water travel times can be calculated from knowledge of the more-specific site conditions listed in favorable condition 4 as well.) Ground-water flux (ellipse (28)) is mentioned in potentially adverse condition 1 of the geohydrology guideline and favorable condition 4 of the geochemistry guideline. Retardation (ellipse (27)) is a factor listed in favorable conditions 2 and 5 and potentially adverse condition 2 of the geochemistry guideline. Tens and probably hundreds of other examples of direct ties to favorable or potentially adverse conditions could similarly be shown if all the influence diagrams were so broken down.

Many of the ties between factors in the influence diagrams with the guideline conditions are more subtle and complex than the preceding paragraph would indicate. For example, again referring to Figure 2-2, waste-package lifetime (ellipse (35)) has ties to favorable conditions 2, 4, and 5 and potentially adverse conditions 1 and 3 of the geochemistry guideline as well as potentially adverse conditions 2 and 3 of the rock-characteristics guideline. Many more examples of these interrelationships could be derived on comparisons of the guideline conditions and the influence diagrams.

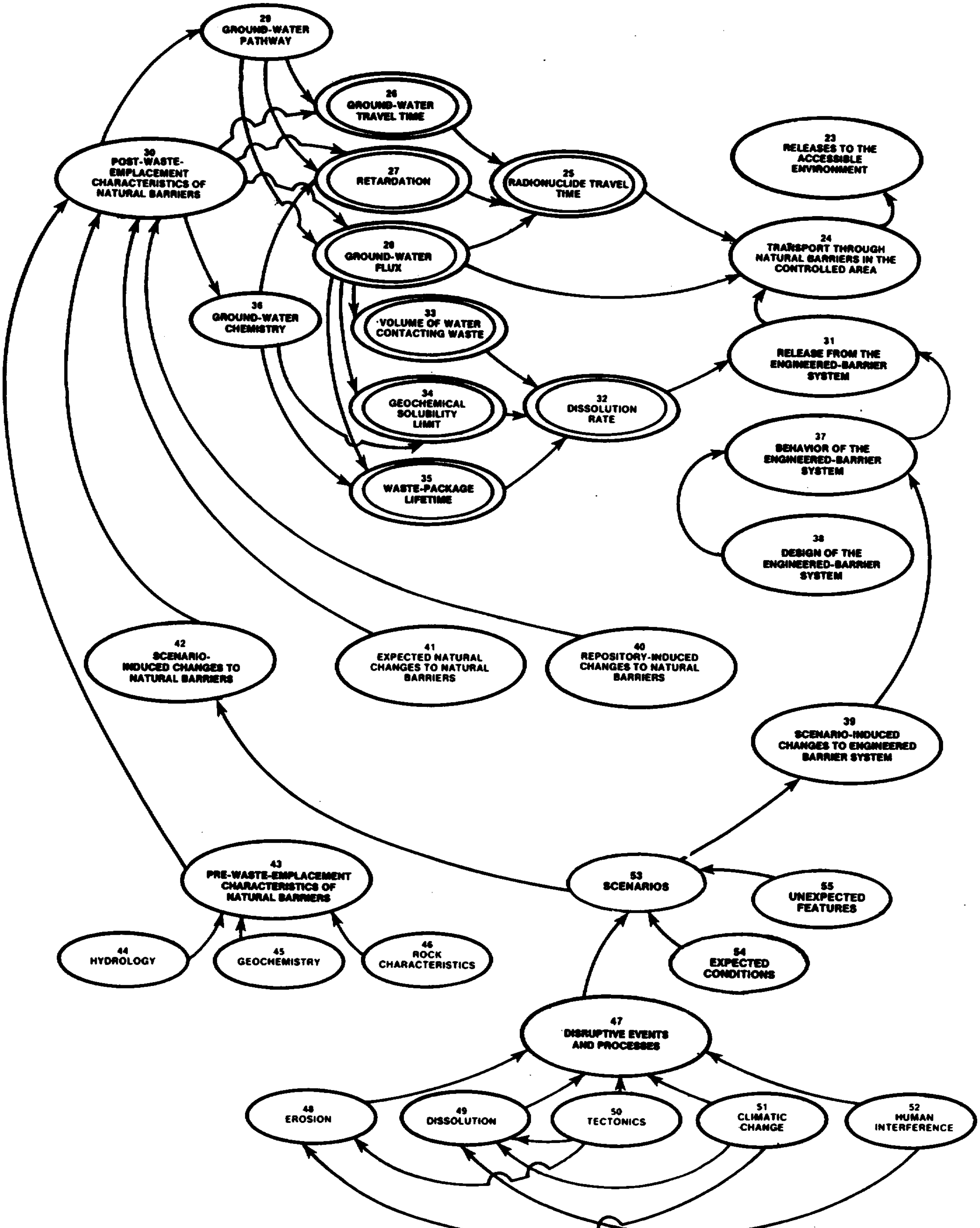

Figure 2-2. Partial diagram showing relationships among factors influencing the numbers of postclosure health effects attributable to the repository. (See Figure 3-2 for complete diagram.)

A final point concerns the implementation guidelines. These guidelines govern the application of all other guidelines in the evaluation of sites and establish general rules to be followed during siting. Of particular relevance here is that they require that primary significance be placed on the postclosure guidelines and secondary significance be placed on the preclosure guidelines. The order of importance assigned to the three groups of preclosure guidelines is as follows: preclosure radiological safety is given the most importance, followed by environment, socioeconomics, and transportation and by ease and cost of siting, construction, operation, and closure. The DOE has met the intent of these requirements in making the value tradeoffs required to establish the multiattribute utility function, as explained in detail in Appendix G (Section G.5).

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Chapter 3

POSTCLOSURE ANALYSIS OF THE NOMINATED SITES

As described in Chapter 2, the formal decision-analysis method known as multiattribute utility analysis was applied to obtain a quantitative comparison of the five sites nominated as suitable for characterization. The application independently evaluated the estimated performance of a repository at each potential site before and after closure. This chapter describes the analysis of postclosure performance.

The components of the postclosure analysis are presented in the various sections of this chapter. Section 3.1 describes the objectives selected to guide the analysis. Section 3.2 summarizes the performance measures defined to quantify the degree to which these objectives are achieved. Section 3.3 discusses the scenarios, or sequences of processes and events, that could affect the postclosure performance of a repository and the judgmental probabilities assigned for each scenario at each site. Section 3.4 describes the performance estimated for each site, expressed in terms of performance measures, for each applicable scenario. Section 3.5 describes the multiattribute utility function developed to integrate the various assessments into an overall postclosure evaluation and the various value judgments for the analysis. Numerical results and sensitivity analyses are presented in Section 3.6. Finally, the conclusions derived from the postclosure analysis are summarized in Section 3.7.

3.1 THE OBJECTIVES HIERARCHY

As noted in Chapter 2, a multiattribute utility analysis is based on the premise that the relative desirability of a site is determined by the extent to which the selection of that site would achieve the siting objectives. The implementation of this logic requires that site-selection objectives be made explicit. For this reason, specific statements of performance objectives for the long-term period after repository closure were developed. Postclosure objectives establish the basis for judging the suitability of a site after repository closure and guide the specification of quantitative performance measures.

Objectives may be stated as very broad and general goals, such as minimizing adverse impacts on the health and safety of the public after closure, or as specific objectives that must be achieved in order for the general objectives to be achieved, such as minimizing the number of health effects attributable to radionuclide releases from a repository. For the application of a multiattribute utility analysis, specific and relatively detailed objectives are required.

Objectives for the postclosure analysis were established by proposing alternative sets of postclosure objectives and then evaluating these alternatives. The basis for generating alternative sets of postclosure objectives was provided by the general siting guidelines published by the U.S.

Department of Energy (DOE) as 10 CFR Part 960 (DOE, 1984). The selection among these alternatives was based on consistency with the intent and history of the siting process as well as on criteria of completeness, nonredundancy, significance, operationality, and decomposability.

The fundamental criterion for judging the postclosure performance of a repository* was assumed to be the extent to which the repository would minimize, after closure, the adverse impacts on public health and safety that could result from exposure to the radionuclides in the waste. This view is consistent with the Nuclear Waste Policy Act of 1982 (the Act), the DOE siting guidelines, and regulations established by other agencies. The length of this postclosure period has been established by the U.S. Environmental Protection Agency in 40 CFR Part 191, Subpart B (EPA, 1985), to be 10,000 years after closure. In evaluating the postclosure performance of a repository, it is necessary to consider not only performance under the conditions expected for the first 10,000 years after closure, but also the effects of potentially disruptive natural phenomena and inadvertent human interference. In addition, the implementation provisions of the siting guidelines (10 CFR 960.3-1-5) call for comparisons of the undisturbed performance of alternative sites for 100,000 years to support the recommendation of sites for the development of repositories. The DOE believes that sites capable of meeting the stringent requirements for these time periods would continue to provide safe isolation for even longer time periods.

Accordingly, two objectives were defined:

1. Minimize the adverse health effects attributable to the repository during the first 10,000 years after closure.

2. Minimize the adverse health effects attributable to the repository during the period 10,000 to 100,000 years after closure.

The term "minimize" is used in the statements of the above objectives to indicate that, all other things being equal, a repository system that leads to the fewest postclosure health effects would be preferred. It must be recognized that preclosure considerations (such as the desire to avoid significant environmental impacts and economic costs) may make strict minimization (i.e., selecting the site that would produce the smallest number of postclosure health effects regardless of costs or other preclosure considerations) undesirable. Performance against the above objectives may have to be traded off to obtain improved performance against preclosure objectives. Making any necessary tradeoffs of one objective against another in a way that is consistent with the fundamental values of our society is one of the principal goals of multiattribute utility analysis.

*In this chapter, terms like "repository performance" mean the performance of the total repository system--that is, the geologic setting at the site and the engineered barriers, all acting together to contain and isolate the radioactive waste.

Defining objectives in terms of health effects ensures that proper consideration will be given to the various means by which sites might minimize adverse health effects. Alternative site-selection objectives, such as "maximize the physical separation of radioactive waste from the accessible environment after closure" or "maximize the flexibility to use engineered barriers to ensure compliance with applicable regulations" derive their importance from being means to minimize health effects. Basing objectives on end consequences ensures that criteria defined in terms of the means for achieving the desired consequences will be taken into account and assigned an appropriate degree of importance.

The two postclosure objectives defined above could be combined into a single objective of minimizing health effects for 100,000 years after repository closure. Alternatively, these objectives could be further split into subobjectives that cover shorter time intervals, such as minimizing health effects from 0 to 1000 years, from 1000 to 10,000 years, from 10,000 to 25,000 years, and so forth. Because there is little evidence that health effects would occur at appreciably different times for different repository sites, only two time periods were considered.

Figure 3-1 shows the two postclosure objectives displayed as part of a simple objectives hierarchy. The hierarchy indicates that the two lower-level objectives must be achieved in order to achieve the higher-level objective of minimizing adverse impacts on public health and safety after closure.

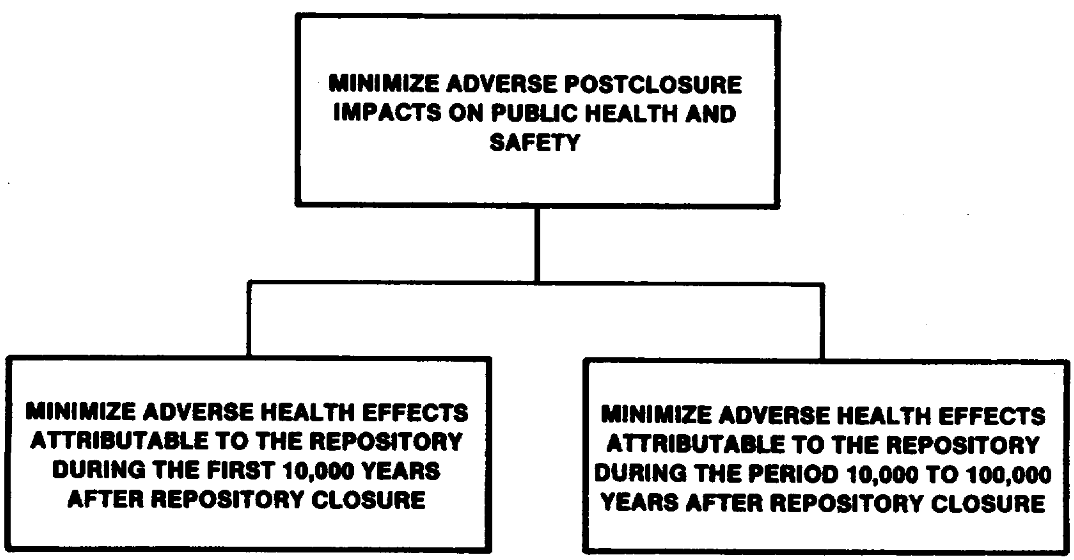

Figure 3-1. Postclosure objectives hierarchy.

3.2 PERFORMANCE MEASURES

The second step in the postclosure analysis consisted of defining performance measures to quantify the degree to which a site achieves each postclosure objective. According to the multiattribute utility theory, performance measures can be either direct or indirect (surrogate) measures of objectives. For example, the following would be a direct measure for the objective of minimizing the health effects attributable to the repository: the total number of premature deaths from cancer that are attributable to the repository. However, it is sometimes difficult or impractical to use direct performance measures. In this analysis, the use of direct measures, such as the example given above, was judged impractical because the size and the geographic distributions of populations, dietary habits, and ways of life will undoubtedly change over a period of 10,000 years. These factors, which must be known to estimate health effects, cannot be usefully predicted over such long periods of time. For this reason, appropriate surrogates were sought to serve as more useful measures of performance.

3.2.1 METHODS USED IN THE DEVELOPMENT OF PERFORMANCE MEASURES

The first step in the development of performance measures for the postclosure analysis was the identification of the key factors that affect the number of postclosure health effects that might result from a repository at a given site. To help summarize these factors and to illustrate the relationships among them, a diagram was constructed. Called an "influence diagram," this diagram shows the major cause-and-effect and other influencing relationships among the identified factors.

The postclosure influence diagram is shown in Figure 3-2. Only a brief explanation is given here because a detailed description and explanation of the relationships represented in the diagram appear in Appendix C. Shown at the top of the diagram is a direct measure of postclosure performance in any given time period--the number of adverse health effects attributable to the repository. All of the factors shown below this factor influence it, either directly or indirectly. For example, the diagram shows that two factors, the number of people exposed (the population at risk) and the dose received by each person, directly influence the number of health effects. Radiation doses, in turn, indirectly depend on radionuclide releases to the accessible environment and on the transport, retardation, dispersion, accumulation, and uptake of those radionuclides along a variety of environmental pathways. The doses received by people result from ingestion, inhalation, and immersion.

Of the various factors shown in the influence diagram, the factor defined as "releases to the accessible environment" was selected to serve as a surrogate for health effects. There were two reasons for this choice. The first reason is practicality. Even though the diagram shows a number of factors whose influence on health effects is more direct than that of releases (examples are radiation doses received through ingestion, inhalation, and immersion), these factors cannot be estimated for the next 10,000 to 100,000 years. As mentioned, it is not possible to predict the long-term changes in the environment, population distributions, and behavioral patterns that determine how releases result in the doses received by people. Although there may

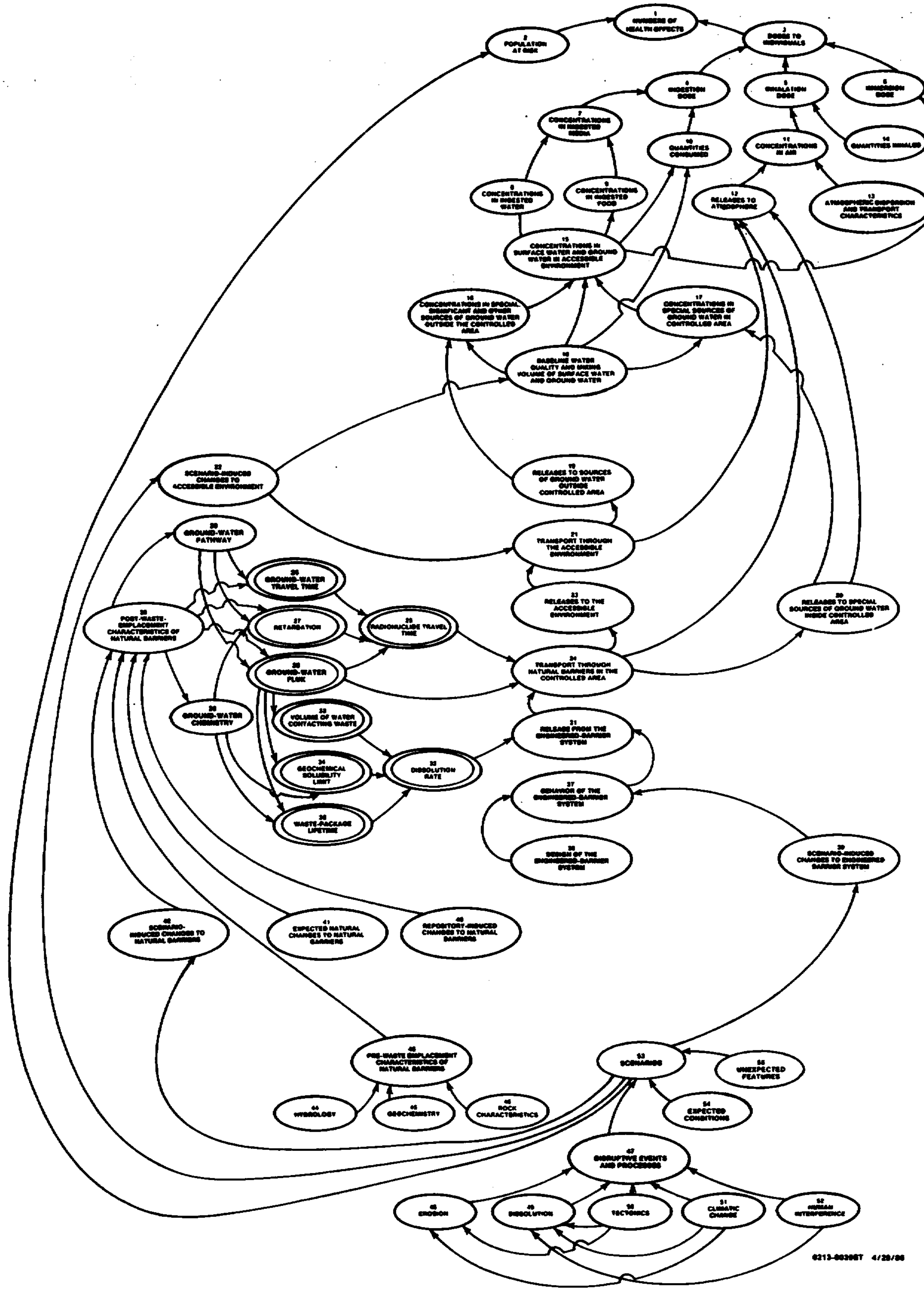

Figure 3-2. Relationships among the factors influencing the numbers of postclosure health effects attributable to the repository.

be distinctions among the sites now in terms of population size and land use, these distinctions cannot be reasonably extrapolated far into the future. An argument that, over the next tens of thousands of years, releases at one site will be less hazardous than the same releases at another site would be highly speculative.

The second reason for selecting releases as a surrogate for health effects is consistency with the EPA standards (40 CFR Part 191). The primary containment requirements of the EPA standards, in particular Table 1 of Appendix A of 40 CFR Part 191, specify the allowable cumulative releases of radionuclides to the accessible environment per 1000 metric tons of heavy metal (MTHM) for 10,000 years after repository closure. These release limits were established by the EPA after evaluating the expected performance of geologic repositories in generic basalt, granite, salt, and tuff host rocks. They are based on (1) very general models of environmental transport; (2) a linear, nonthreshold dose-effect relationship between radiation exposures and premature deaths from cancer; and (3) current population distributions and death rates. For each 1000 MTHM, the overall cumulative-release limit specified by the EPA represents the potential for approximately 10 premature deaths from cancer during the first 10,000 years after repository closure. The EPA has, in effect, provided scaling factors that relate cumulative releases to premature deaths from cancer. Thus, releases expressed as fractions or multiples of the overall EPA release limit provide a useful surrogate for health effects.

3.2.2 PERFORMANCE MEASURES SELECTED FOR THE ANALYSIS

Selecting radionuclide releases as a surrogate for postclosure objectives leads to the following performance measures:

1. Cumulative releases of radionuclides to the accessible environment during the first 10,000 years after repository closure.

2. Cumulative releases of radionuclides to the accessible environment during the period 10,000 to 100,000 years after repository closure.

To account for the different radionuclides that will be disposed of in the repository, releases were quantified in terms of the release limits specified by the containment requirements of 40 CFR Part 191, Subpart B. As noted in the preceding section, Table 1 in Appendix A of 40 CFR Part 191 specifies, in terms of curies per 1000 MTHM, the allowable cumulative releases of individual radionuclides for 10,000 years after repository closure. As explained by Note 6 in Appendix A of 40 CFR Part 191, a cumulative release of a mixture of radionuclides can be compared against the EPA limits by dividing the release quantity for each radionuclide in the mixture by the limit specified in the table and summing the result. A repository at each of the nominated sites was assumed to contain 70,000 MTHM. Thus, the estimated releases from a repository at a given site can be expressed as a fraction or multiple of the same weighted total allowed by the EPA limits. The statement "the releases estimated for the repository during the first 10,000 years are equal to 0.1 of the EPA limits" means that the weighted sum of the cumulative releases of various radionuclides over this period is estimated to be one-tenth of the EPA limit. The EPA limits were also used as a basis to establish a scale for measuring cumulative releases during the period 10,000 to 100,000 years after closure. Thus, the statement "cumulative releases of radionuclides for 10,000 to 100,000 years after repository closure are estimated to be 0.1 of the EPA limits" means that the cumulative releases over this 90,000-year period are estimated to be one-tenth of the EPA limits for the first 10,000 years.

Table 3-1 summarizes the correspondence between postclosure objectives and performance measures and the units in which performance is expressed. As noted in the table, y_1 is used to designate the performance measure for the first 10,000 years and y_2 the performance measure for the second time period, 10,000 to 100,000 years.

Table 3-1. Objectives and performance measures for the postclosure period

Objective		Performance measure	Units
1. Minimize the total number of health effects attributable to the repository during the first 10,000 years after closure	y_1:	Cumulative releases of radionuclides to the accessible environment during the first 10,000 years after repository closure	Multiples of the release limits specified by Table 1 and Note 6 of Appendix A of 40 CFR Part 191 for the first 10,000 years
2. Minimize the total number of health effects attributable to the repository during the period 10,000 to 100,000 years after closure	y_2:	Cumulative releases of radionuclides to the accessible environment during the period 10,000 to 100,000 years after repository closure	Multiples of the release limits specified by Table 1 and Note 6 of Appendix A of 40 CFR Part 191 for the first 10,000 years

3.3 SCENARIOS

The releases that will occur if the repository is located at a particular site obviously depend on the processes and events that will occur at that site, such as major earthquakes. The influence of such processes and events on releases, and therefore health effects, is represented in the influence diagram (Figure 3-2) by the ellipse labeled "scenarios." The scoring of each site in terms of releases was based on specific scenarios. Credible scenarios were developed by identifying the different processes, events, and conditions that might affect the performance of a repository at a site.

3.3.1 METHOD USED FOR IDENTIFYING SCENARIOS

The set of scenarios used in estimating releases was developed through a sequence of steps conducted by a panel of technical specialists under the general guidance of the methodology lead group. The various participants are identified in Tables A-1 and A-2 of Appendix A. First, the various conditions that could affect postclosure performance were identified. As shown in the influence diagram of Figure 3-2, disruptive scenarios can affect health effects by (1) altering the characteristics of the engineered barriers so as to change the rate and the magnitude of the release of radionuclides; (2) altering the characteristics of the natural barriers so as to change the rate of radionuclide transport to the accessible environment; (3) altering the accessible environment in ways that affect the extent to which the released radionuclides change the concentration of radionuclides in sources of ground water; and (4) altering the population at risk. Because the last two mechanisms do not affect releases, the development of scenarios focused on the mechanisms that affect releases from the engineered-barrier system and transport through the natural barriers in the controlled area.

As shown in Figure 3-2, the releases from a repository are affected by such factors as the ground-water travel time, flux, and chemistry as well as the rates of radionuclide dissolution and retardation. Conditions relating to or altering these factors thus potentially affect releases. Three categories of conditions were considered: (1) expected conditions (nominal case), (2) unexpected features, such as undetected faults, and (3) disruptive processes and events. Many studies in the past several decades have attempted to identify and evaluate processes and events that may affect the performance of a repository. This literature was reviewed to aid the identification of relevant conditions. In accordance with 40 CFR Part 191, Subpart B, only the disruptive processes and events that might occur in the first 10,000 years after closure were considered. In all cases, however, the effects of postulated conditions were evaluated for both the first 10,000 years and the period 10,000 to 100,000 years.

To identify scenarios that pose a credible risk to the performance of a repository, the individual and combinations of conditions falling into the above categories were screened by applying two criteria. First, any process or event judged to be incapable of increasing releases by more than 10 percent from those for expected conditions, regardless of the other conditions that might occur, was excluded, unless the process or event was also judged to have a high probability (more than 1 chance in 10) of occurrence. Second, a process or event judged to have a probability of less than 1 chance in 10,000 over 10,000 years was eliminated unless it was judged possible that the occurrence of the scenario might increase releases by a very great amount (so that the product of the probability and the factor by which releases might be increased would be greater than 0.01). When there was reasonable doubt as to whether a process or event should be eliminated, it was retained.

The final step in the process was to construct sequences of the remaining events and processes that might lead to impacts on repository performance. Table 3-2 lists the scenarios that were developed. The scenarios were judged to encompass all of the significant phenomena, processes, or events that might occur at the sites. The scenarios are mutually exclusive because it was assumed that the occurrence of a scenario implied the occurrence of only the events specified by the scenario (and none of the events specified by other scenarios). Although scenarios involving combinations of the conditions indicated in the table were considered, such scenarios were eliminated in the screening. A detailed explanation of the scenarios and their development can be found in Appendix C.

Table 3-2. Potentially significant scenarios

Scenario	Description
1	Nominal case (expected conditions)
2	Unexpected features
3	Repository-induced dissolution of the host rock
4	Advance of a dissolution front
5	Movement on a large fault inside the controlled area but outside the repository
6	Movement on a large fault within the repository
7	Movement on a small fault inside the controlled area but outside the repository
8	Movement on a small fault within the repository
9	Movement on a large fault outside the controlled area
10a	Extrusive magmatic event that occurs during the first 500 years after closure
10b	Extrusive magmatic event that occurs 500 to 10,000 years after closure
11	Intrusive magmatic event
12	Large-scale exploratory drilling
13	Small-scale exploratory drilling
14	Incomplete sealing of the shafts and the repository

3.3.2 ASSIGNMENT OF PROBABILITIES TO SCENARIOS

Each scenario was assigned probabilities that indicate the judged likelihood of occurrence at each site. These probabilities were assessed by a panel of technical specialists selected for their expertise in the processes and events that could affect the performance of the repository. The members of the panel are listed in Table A-2 of Appendix A.

Care must be taken in generating judgmental probabilities if the probabilities are to reflect accurately the underlying knowledge and beliefs of the persons who generate them. To help avoid errors in assessed probabilities, panel members were introduced to the theory of judgmental probability and apprised of the biases that experiments (e.g., Kahneman, Slovic, and Tversky, 1982) have shown can produce distortions in probability estimates. Panel members practiced making probability estimates by using a broad range of sample questions. The probabilities estimated by each panel member were then tabulated and compared with the actual answers to the sample questions. This permitted each panel member to test his or her skill at assessing judgmental probabilities and provided an increased awareness of the need to avoid potential biases that might affect the assessments.

The process by which the panel made judgmental probability estimates consisted of several steps. At the outset, the panel members reviewed the available information on the scenarios and the estimates of their probabilities. Then, using his or her professional judgment, each panel member individually provided initial best-judgment, high, and low estimates of the probability of occurrence of a given scenario at a particular site. The high probability was that person's recommended upper bound for the probability. Similarly, the low-probability estimate was the panel member's recommended lower bound for the probability. After the various probability estimates were tabulated, summary statistics were computed and presented to the panel. The results were then discussed by the panel members, including the merits of higher versus lower estimates. After the discussion, some members elected to modify some of their initial estimates. Finally, by consensus, the panel recommended a set of probabilities to be used in the analysis. Often times, the geometric mean of the suite of individual assessments was selected for the recommended base-case probability, and the highest of the individual high-probability estimates and the lowest of the individual low-probability estimates were selected for the high and the low probabilities.

Table 3-3 shows the judgmental probabilities recommended by the panel for the various site-specific scenarios. Probabilities were not assessed if, in the judgment of the panel, the occurrence of the scenario at a site would not significantly affect the performance of the repository or if the maximum probability of the scenario was judged to be less than one chance in 10,000 over 10,000 years. The decision not to assess probabilities in such cases represented a more rigorous application of the screening criteria that had been applied earlier. Where probabilities were assessed, three probability values--high, base-case, and low--were estimated. All such probabilities were assigned as direct judgments, with the exception of the probability for the nominal case (scenario 1). The probability of this scenario was calculated for each site by summing the probabilities of all the other scenarios and subtracting the result from unity.

As can be seen from Table 3-3, scenario 1 (the nominal case) was viewed as the most likely scenario at all sites (between 96 and 98 percent of the probability in the base case). Scenario 2 (unexpected features) was judged to be the next most likely scenario to occur at all sites, with 1.3 to 2.4 percent of the probability of the base case. Of the disruptive scenarios, exploratory drilling was regarded to be more likely to occur at the salt sites. Incomplete sealing of the shafts and the repository was viewed to be more likely at the Hanford site than at the other sites. Movement on a large fault of sufficient magnitude to affect expected repository performance was judged most likely at the Hanford site. A magmatic event of sufficient magnitude to affect expected repository performance was judged most likely at the Yucca Mountain site.

3.4 SITE SCORING

Scoring a site against the postclosure performance measures requires estimating the cumulative releases that would occur from a repository at that site under each of the applicable scenarios. Estimating cumulative releases in the two postclosure time periods is extremely difficult because of limited data and the limited understanding of the mechanisms by which releases can occur. Various performance-assessment models have been developed to estimate releases from the repository over time. Although the results produced by these models are regarded as providing useful bounds, the models are known to be simplifications of the complex processes that are involved.

A more appropriate approach is to augment the results of analyses based on release models with assessments of the accuracies and limitations of the models. This can be accomplished by obtaining direct judgmental assessments

Table 3-3. High, base-case, and low probabilities assessed for scenarios[a]

Scenario[b]	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
1[c]	1 9.8×10^{-1} 8.0×10^{-1}	1 9.8×10^{-1} 8.0×10^{-1}	1 9.8×10^{-1} 8.0×10^{-1}	1 9.6×10^{-1} 6.4×10^{-1}	1 9.8×10^{-1} 8.0×10^{-1}
2	1.0×10^{-1} 1.4×10^{-2} 0	1.0×10^{-1} 1.6×10^{-2} 0	1.0×10^{-1} 1.3×10^{-2} 0	2.5×10^{-1} 2.4×10^{-2} 0	2.0×10^{-1} 1.9×10^{-2} 0
3	NC	NC	NC	NC	NC
4	NC	NC	NC	NC	NC
5	NC	NC	NC	1.0×10^{-2} 3.2×10^{-3} 1.0×10^{-5}	NA
6	NC	NC	NC	3.2×10^{-4} 3.2×10^{-4} 3.0×10^{-5}	NA
7	NA	NA	NC	NA	NA
8	NC	NC	NC	NA	NA
9	NA	NA	NA	NA	NA
10a	NC	NC	NC	NC	5.0×10^{-6} 5.0×10^{-8} 1.0×10^{-10}
10b	NC	NC	NC	NC	1.0×10^{-4} 1.0×10^{-6} 1.0×10^{-10}
11	NC	NC	NC	NC	NC
12	1.0×10^{-1} 2.0×10^{-3} 1.0×10^{-5}	1.0×10^{-1} 2.0×10^{-3} 1.0×10^{-5}	1.0×10^{-1} 2.0×10^{-3} 1.0×10^{-5}	NC	NC
13	NA	NA	NA	NA	NA
14	1.0×10^{-3} 1.0×10^{-4} 1.0×10^{-5}	2.0×10^{-3} 2.0×10^{-4} 2.0×10^{-5}	5.0×10^{-3} 5.0×10^{-4} 5.0×10^{-5}	1.0×10^{-1} 1.0×10^{-2} 1.0×10^{-3}	NA

[a]Key: NA = scenario judged to have an insignificant effect on releases; NC = scenario judged to be not credible.

[b] See Table 3-2 for descriptions.

[c] The high probability for scenario 1 is equal to 1 minus the sum of the low probabilities of scenarios 2 through 14. The low probability for scenario 1 is equal to 1 minus the sum of the high probabilities of scenarios 2 through 14. The probabilities listed for scenario 1 are rounded off.

of releases from experts who understand the analyses, know the extent and limitations of the data for the sites, and appreciate the complexity of the processes by which releases can occur at a given site.

3.4.1 METHOD OF OBTAINING ASSESSMENTS OF RELEASES

Judgmental assessments of releases were obtained in a two-step process. The first step was to clarify the relationship between releases and the basic hydrologic, geochemical, and geomechanical characteristics of a site. This step was performed by members of the methodology lead group and technical specialists from the postclosure analysis group. The technical specialists were familiar with the processes by which radionuclides could be released from a repository, the available conceptual models for predicting radionuclide release and transport, and the results of analyses conducted with these models. They were also familiar with the level of conservatism in the assumptions incorporated into the release models (when information to support more-realistic assumptions is lacking) and the processes that have been omitted from the models; an example of the latter is the effect of waste-generated heat on the host rock and surrounding units in the repository. The purpose of this step was to state explicitly the best current scientific judgment about the relationship between site characteristics and radionuclide releases for the benefit of those less familiar with the subject.

To make these judgments explicit, descriptions of six hypothetical sites were developed. These hypothetical sites ranged from a site with relatively poor characteristics to one with extremely good characteristics for waste isolation. Consensus estimates of the releases that would occur during each time period from a repository at each of the hypothetical sites were then provided by persons with the most expertise in the assessment of releases. The hypothetical site descriptions were then modified and generalized until an orderly correspondence between releases and site descriptions was obtained.

Figures 3-3 and 3-4 show the relationships between site characteristics and estimated releases. Each figure shows a scale of 0 to 10, with the left-hand side defined in terms of releases expressed as multiples of the EPA release limits and the right-hand side defined in terms of site characteristics. It must be emphasized that various combinations of site characteristics can lead to the same magnitude of releases; that is, the descriptions on the right of the scale are not unique (see Appendix B).

During the first 10,000 years after repository closure, as shown on the left of the scale in Figure 3-3, the releases estimated for the hypothetical sites ranged from a value 10,000 times lower than the EPA release limits to 10 times higher than the EPA limits. This range was judged to encompass all levels of releases that could occur at any of the nominated sites. For the period 10,000 to 100,000 years after closure, release estimates ranged from a value 1000 times lower than the EPA limits to 100 times higher than the limits, as shown in Figure 3-4. This range was similarly judged to encompass all levels of releases that could occur at any of the nominated sites during that time period. A 0 to 10 scale was used to simplify the association of site characteristics with releases.

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the First 10,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.0001	10 9	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are insignificant. This judgment is based on a combination of site characteristics that implies an extremely limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 1 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that very strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 200,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.001	8 7	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are extremely small. This judgment is based on a combination of site characteristics that implies a very limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 3 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 150,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.01	6 5	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are very small. This judgment is based on a combination of site characteristics that implies a limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 10 percent of the EPA release limits because of a very low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 100,000 years because of very favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a very long ground-water travel time.
0.1	4 3	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 30 percent of the EPA release limits because of a low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 50,000 years because of favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a long ground-water travel time.
1	2 1	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies high potential for releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 100 percent of the EPA release limits because of a high volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that weakly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is less than 10,000 years because of moderate retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a moderate ground-water travel time.
10	0	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are extremely significant. This judgment is based on a combination of site characteristics that implies an extremely high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 1000 percent of the EPA release limits because of an extremely high volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that enhance waste dissolution. • The median travel time to the accessible environment of any key radionuclide is less than 3000 years because of little retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a short ground-water travel time.

NOTE: It must be kept in mind that the set of site characteristics that leads to any given score is not unique. Equivalent combinations of performance factors are given in Table 6-1.

Figure 3-3. Scale used to aid the judgmental estimation of releases during the first 10,000 years after repository closure.

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the Time Period 10,000 to 100,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.001	10 9	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are insignificant. This judgment is based on a combination of site characteristics that implies an extremely limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground-water in 90,000 years is about 10 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that very strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 300,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.01	8 7	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are extremely small. This judgment is based on a combination of site characteristics that implies a very limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 30 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 250,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.1	6 5	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are very small. This judgment is based on a combination of site characteristics that implies a limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 100 percent of the EPA release limits because of a very low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 200,000 years because of very favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a very long ground-water travel time.
1	4 3	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 300 percent of the EPA release limits because of a low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 150,000 years because of favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a long ground-water travel time.
10	2 1	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies a high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 1000 percent of the EPA release limits because of a high volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that weakly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 100,000 years because of moderate retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a moderate ground-water travel time.
100	0	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are extremely significant. This judgment is based on a combination of site characteristics that implies an extremely high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 10,000 percent of the EPA release limits because of an extremely high volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that enhance waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 10,000 years because of little retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a short ground-water travel time.

NOTE: It must be kept in mind that the set of site characteristics that leads to any given score is not unique. Equivalent combinations of performance factors are given in Table B-2.

Figure 3-4. Scale used to aid the judgmental estimation of releases occurring during the period 10,000 to 100,000 years after repository closure.

The scale was chosen to be geometric (e.g., 0 corresponding to 10 times the release limits, 2 corresponding to the release limits, 4 corresponding to one-tenth the release limit, etc.) to provide greater resolution at low release levels. In view of the performance assessments presented in Section 6.4.2 of the environmental assessments for the nominated sites (DOE, 1986a–e), it was expected that the estimated releases from the sites would be too low for a linear scale to provide sufficient discrimination among sites.

The right-hand sides of the scales shown in Figures 3-3 and 3-4 contain qualitative statements about the factors (shown in Figure 3-2) that affect releases, such as the time of ground-water travel, the ground-water flux, the solubility of key radionuclides, and retardation factors for key radionuclides. As mentioned, there are many combinations of these factors that would lead to the same releases. For example, a site with a long ground-water-travel time and a moderate solubility of key radionuclides may produce the same releases to the accessible environment as one with a moderate ground-water-travel time and a very low solubility of key radionuclides. To account for all of the combinations that are possible, two performance factors were used to summarize the effect of site characteristics on releases:

- A factor, denoted F, for release from the engineered-barrier system; it measures the amount of radionuclides that can be dissolved into the ground water during the period of interest.

- A factor, denoted T_1, for transport through the natural barriers; it measures the time of radionuclide travel from the engineered-barrier system through the natural barriers to the accessible environment under post-waste-emplacement conditions.

These parameters are explained in detail in Appendix B.

3.4.2 PERFORMANCE-MEASURE SCORES

The application of the scales shown in Figures 3-3 and 3-4 to estimate releases was made in a series of workshops attended by the full panel of post-closure technical specialists (see Appendix A). This panel consisted of specialists who were involved in the development of the scales as well as specialists selected for their detailed knowledge of the comparative characteristics of the nominated sites. The sequence of steps conducted at these workshops is summarized below.

For each applicable scenario, beginning with the nominal case, panel members individually provided (by secret ballot) high, best-judgment, and low scores for each site, using the 0 to 10 scales shown in Figures 3-3 and 3-4. Before making these estimates, the panel discussed the relevant characteristics of each site and their significance for releases, using the influence diagram (Figure 3-2) as a guide. The panel then estimated the values of the factors F and T_1 (defined above) for the specified scenario. To obtain an initial best-judgment score for a site for a particular scenario, each member compared the site against the various descriptions shown on the right-hand sides of the scales. The computed estimates of F and T_1 were considered in relation to these descriptions and the equivalent combinations of factors specified in

Tables B-1 and B-2 of Appendix B, taking into account the range of uncertainty in these parameters. If for a given scenario the site was judged to have characteristics comparable to one of the descriptions, it was assigned the even-number score corresponding to that description; if judged to have characteristics that placed it between two of the descriptions, it was assigned the odd-number score between the even numbers corresponding to those descriptions. The high scores of each panel member were to represent site characteristics and releases so favorable that the scorer believed there was only 1 chance in 20 that the actual conditions at the site would be even more favorable. Similarly, the low scores were intended to represent site characteristics and releases so unfavorable that the scorer believed there was only 1 chance in 20 that the actual conditions would be even less favorable.

To reach a decision on a single set of high, base-case, and low scores for a given scenario at a particular site, the panel used a process similar to that used in generating scenario probabilities. The estimates of each panel member were tabulated by representatives of the methodology lead group and reviewed by the panel, with various members presenting arguments for higher or lower estimates. The discussion continued until all members of the panel agreed on a recommended high, base-case, and low score for the scenario. Panel members were then asked to rethink their assessments and to review the data for the site in preparation for a repetition of the scoring exercise two weeks later. The final scores obtained in this second exercise, which differed only slightly from the initial results, are summarized in Table 3-4.

The very low releases implied by the relatively high scores shown in the table should not be surprising. Various preliminary assessments conducted over the last decade have supported the view that, because of the characteristics of the potential host rocks, a loss of waste isolation is highly unlikely. These studies, which used various approaches to analyze the postclosure performance of a repository (e.g., qualitative comparisons of expected performance with natural analogs or quantitative comparisons against regulatory criteria with complex analytical models), have shown that, for carefully selected sites, it is difficult to conceive of credible mechanisms for the loss of waste isolation.

Although additional steps of the multiattribute utility analysis are required to obtain an estimate of the overall postclosure performance for each nominated site, a comparison of the scores in Table 3-4 provides some immediate insights. For each postclosure period, the lowest base-case score given for any salt site for any scenario is as high or higher than the base-case score assigned to the Hanford site for scenario 1 (the nominal case). Thus, in the best collective judgment of the panel, the performance of the salt sites under disruptive conditions will be better (or at least as good) as the performance of the Hanford site under expected conditions. This is not to say that the postclosure performance of the salt sites is guaranteed to be superior to that of the Hanford site or that the releases that could occur from the Hanford site are large enough to be of concern. The high scores for the Hanford site are all 10. Thus, in the judgment of the panel, a repository at the Hanford site may perform better than any of the salt sites under any or all scenarios (since the low scores for the salt sites range from 8 to 4). However, because there is a fairly clear dominance relationship between the salt sites and the Hanford site, it can be expected that the quantitative measure developed to compare the overall postclosure performance of the sites

Table 3-4. High, base-case, and low scores for sites and scenarios[a,b]

Scenario[d]	Davis Canyon[c]		Deaf Smith[c]		Richton Dome[c]		Hanford[c]		Yucca Mountain[c]	
	0-10	10-100	0-10	10-100	0-10	10-100	0-10	10-100	0-10	10-100
1	10 10 8	10 10 8	10 10 8	10 9 7	10 10 8	10 10 8	10 8 4	10 7 4	10 10 5	10 9 5
2	10 9 5	10 9 5	10 8 5	10 8 5	10 9 6	10 9 6	10 6 2	10 6 2	10 8 2	10 8 2
3	NC		NC		NC		NC		NC	
4	NC		NC		NC		NC		NC	
5	NC		NC		NC		10 7 3	10 7 3	NA	
6	NC		NC		NC		9 6 2	9 6 2	NA	
7	NA		NA		NC		NA		NA	
8	NC		NC		NC		NA		NA	
9	NA		NA		NA		NA		NA	
10a	NC		NC		NC		NC		7 2 0	9 7 3
10b	NC		NC		NC		NC		7 3 0	10 7 2
11	NC		NC		NC		NC		NC	
12	10 9 6	10 9 6	10 9 6	10 9 6	10 8 4	10 8 4	NC		NC	
13	NA		NA		NA		NA		NA	
14	10 10 8	10 10 7	10 10 7	10 9 6	10 10 7	10 10 7	10 7 3	10 7 3	NA	

[a] Key: NA = scenario judged to have insignificant effect on releases; NC = scenario judged to be not credible.
[b] Higher scores are more desirable than lower scores.
[c] The numbers 0-10 and 10-100 represent 0 to 10,000 years after closure and 10,000 to 100,000 years after closure, respectively.
[d] See Table 3-2 for descriptions.

will rank the Hanford site lower than the salt sites. Analogous dominance arguments involving other pairs of sites cannot be made on the basis of the scores in Table 3-4.

3.5 MULTIATTRIBUTE UTILITY FUNCTION

The preceding sections described the low, base-case, and high scores assigned to quantify repository performance for each nominated site in the nominal case and for various disruptive scenarios. As described, judgmental scores were assigned to estimate performance in the first 10,000 years after closure and in the period 10,000 to 100,000 years after closure. This section discusses the various value judgments that are required for a logical aggregation of these scores to obtain an overall measure of the postclosure performance of each site. The value judgments for the analysis were made by the senior managers from the DOE's Office of Civilian Radioactive Waste Management (see Table A-4 of Appendix A).

Three steps are necessary to aggregate the various postclosure scores. First, it is necessary to account for the relative desirability of achieving higher versus lower scores for each performance measure. Single-attribute utility functions are used to quantify the desirability of various performance-measure scores. Second, the relative importance of achieving a given score in the first 10,000 years after closure as compared to achieving that same score in the next 90,000 years must be specified. The relative importance of performance in the two time periods is addressed by assigning scaling factors. Finally, the scores assigned to each site for various scenarios must be aggregated to obtain a single number, a so-called expected utility, that represents the expected postclosure performance of the site.

3.5.1 ASSESSMENT OF SINGLE-ATTRIBUTE UTILITY FUNCTIONS

To understand why single-attribute utility functions are needed, consider the definitions of the postclosure performance measures. It is clear that higher scores for the performance measures are more desirable, all other things being equal. For example, a site that scores 10 would be more desirable than an otherwise identical site that scores 8 for the same scenario, and a site that scores 8 would be more desirable than a twin that scores 6. It is not immediately clear, however, how much more desirable the higher-scoring site would be. For example, would a site that scores 8 be halfway between a site that scores 10 and a site that scores 6? The answer depends on two issues. The first is the relative magnitude of the releases that could occur at each site; the second is the level of concern about those releases.

The first issue--the relative magnitude of releases from sites with various scores--is easily resolved by examining the definitions of the performance-measure scales. As noted in Section 3.4, the scales are geometric. A site that scores 6 for the first 10,000 years is estimated to produce releases 100 times lower than the EPA limits; a site that scores 8 is estimated to produce releases 1000 times lower than the limits; and a site that scores 10 is estimated to produce releases 10,000 times lower than the limits. Thus, equal increases in scores (e.g., going from 6 to 8 versus from 8 to 10) do not produce equal increments in estimated releases. The marginal reduction in releases per unit increase in score decreases with increasing scores.

The second issue, the significance of various release magnitudes, requires value judgments. The single-attribute utility functions account for both the scales established for measuring performance (the first issue) and the value of achieving various levels of performance on those scales (the second issue).

The method used for assessing the single-attribute utility functions is the so-called midpoint method. The following notation will help to simplify the description of this method. Let y^{min} denote the smallest possible releases from a repository site (for simplicity, y^{min} was assumed to be zero) and let y^{max} denote the largest releases. In the assessment of a utility function for the first time period, y^{max} was taken to be ten times the EPA limits, in accordance with the performance-measure scale of Figure 3-3. The utilities of y^{max} and y^{min} are denoted by $U_1(y^{max})$ and $U_1(y^{min})$. Various release levels between y^{min} and y^{max} were then considered until one was found, denoted y', such that it was judged equally desirable to change a site with y^{max} releases to the level y' as it would be to change a site with y' releases to the level y^{min}. The release level y' is called the midpoint, or mid-utility point, because the utility of this level is midway between the utilities of the other two outcome levels (i.e., $U_1(y')$ is one half of $U_1(y^{min}) + U_1(y^{max})$). The same process was repeated to find other mid-utility points (e.g., the mid-utility point between y' and y^{max}) until enough points were identified to permit fitting a smooth curve. Finally, the curve was scaled so that the utility of zero releases (i.e., where $y = y^{min} = 0$), would be 100 and the utility of releases at the EPA limits (i.e., where $y = 1$), would be 0.

The same process was followed to obtain the utility curve for releases during the second period, 10,000 to 100,000 years after closure. In the second time period, releases could be as great as 100 times the EPA limits, whereby the definition of y^{max} was changed accordingly. Also, the utility curve was scaled so that the utility of releases equal to nine times the limit for the first 10,000 years would be zero.

The utilities obtained in the two encoding exercises were found to be very nearly proportional to the magnitude of releases. Figures 3-5 and 3-6 show the utilities obtained for the first and the second time periods, respectively, plotted as functions of cumulative releases during those periods. Because the deviations from linearity were very small, the DOE managers elected to assume direct proportionality between releases and utility. Specifically, linearity implies that

$$U_1(y_1) = 100(1 - y_1) \tag{3-1}$$

and

$$U_2(y_2) = 100(1 - y_2/9). \tag{3-2}$$

A linear relationship is an intuitive result, since it might be expected that postclosure releases would be roughly proportional to radiological health effects and that the desirability of a site would be directly proportional to decreases in radiological health effects.

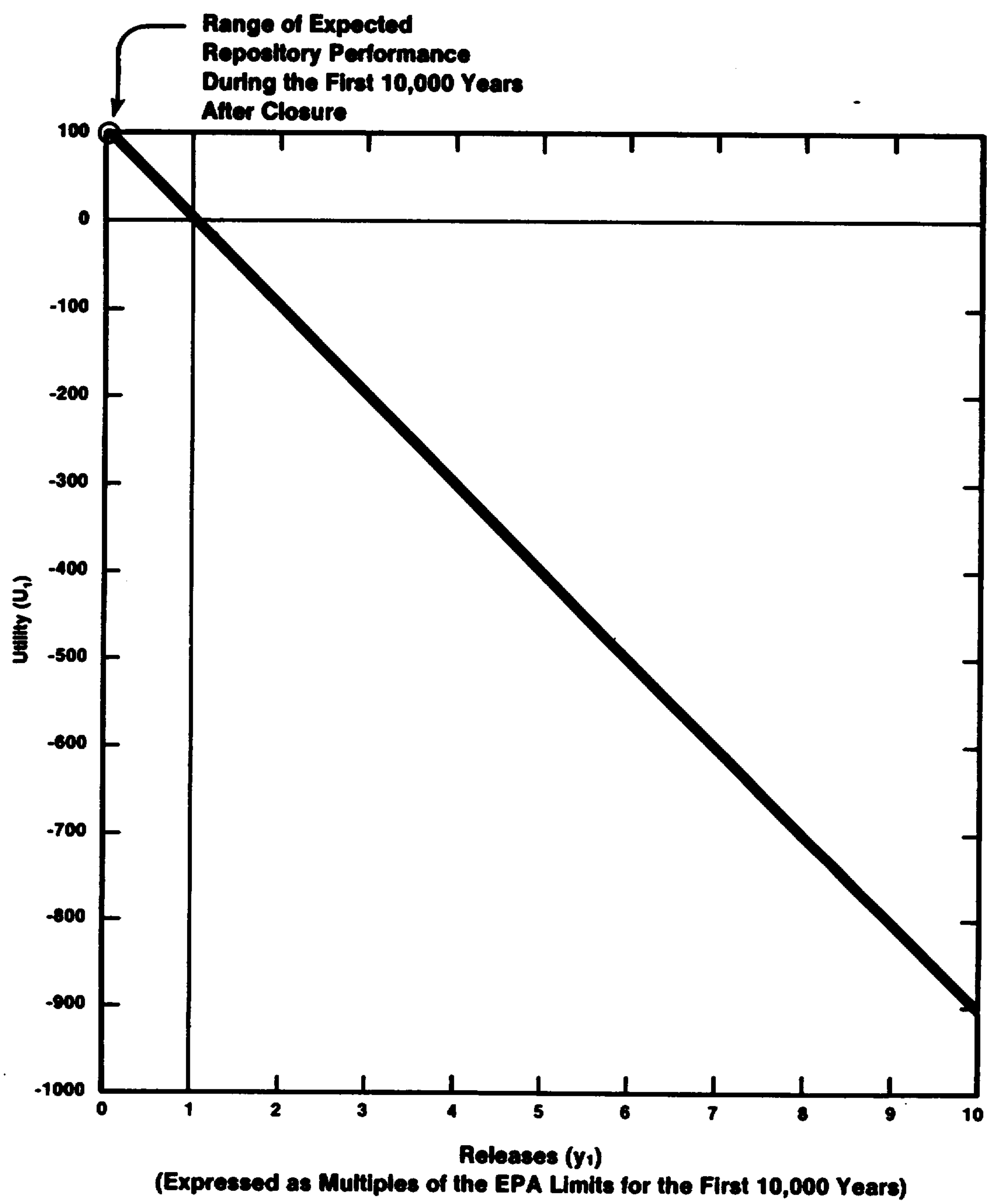

Figure 3-5. Assessed utility of cumulative releases during the first 10,000 years after repository closure.

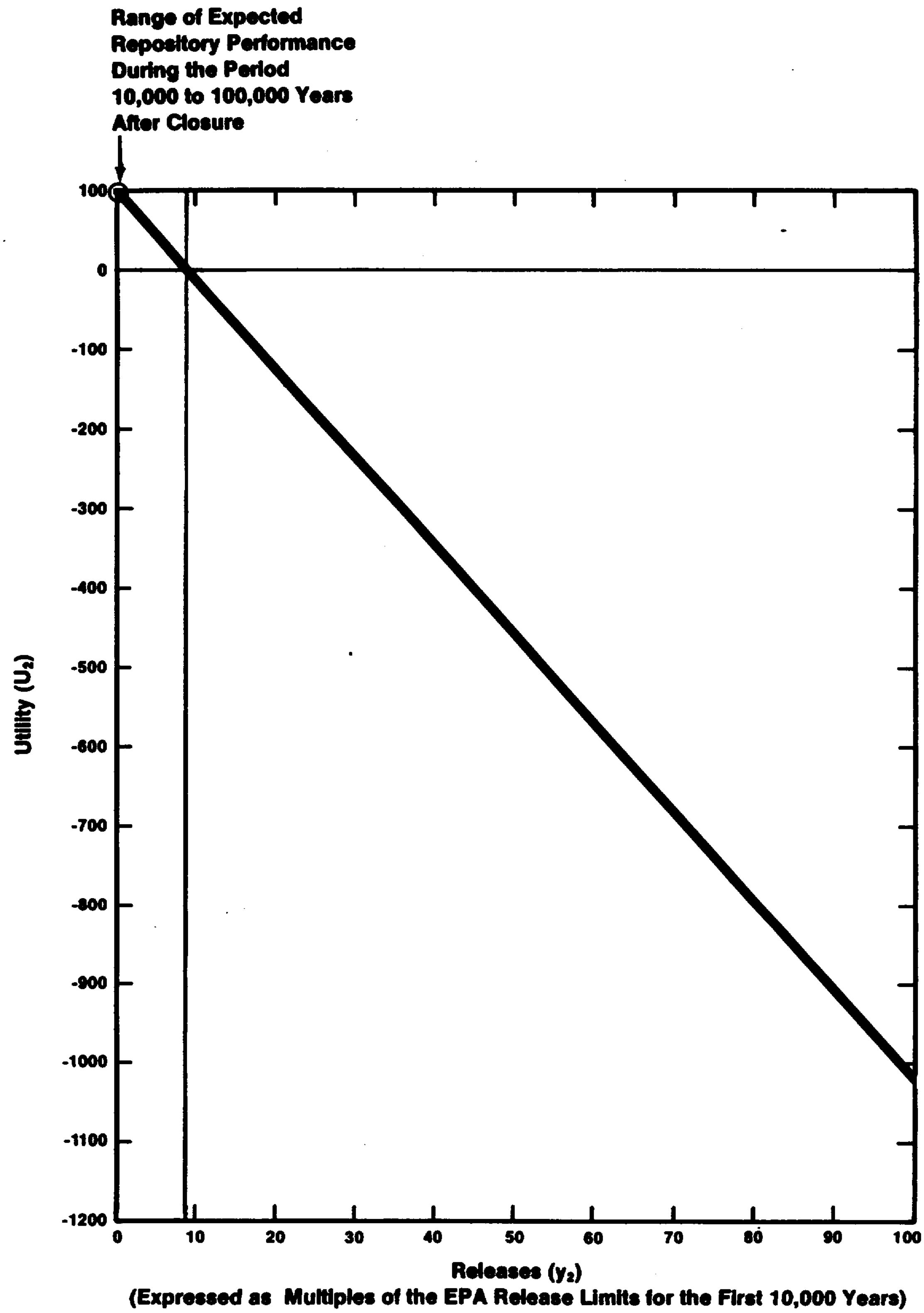

Figure 3-6. Assessed utility of cumulative releases during the period 10,000 to 100,000 years after repository closure.

When utilities that are proportional to releases are plotted as a function of scores that represent geometrically increasing releases, the curves shown in Figures 3-7 and 3-8 are obtained. Because of the geometric relationship between scores and releases, the utility function increases rapidly at first, but then levels out as further increases in score produce only very small reductions in the magnitude of releases. The utilities and the releases corresponding to various scores for each time period are shown in Table 3-5.

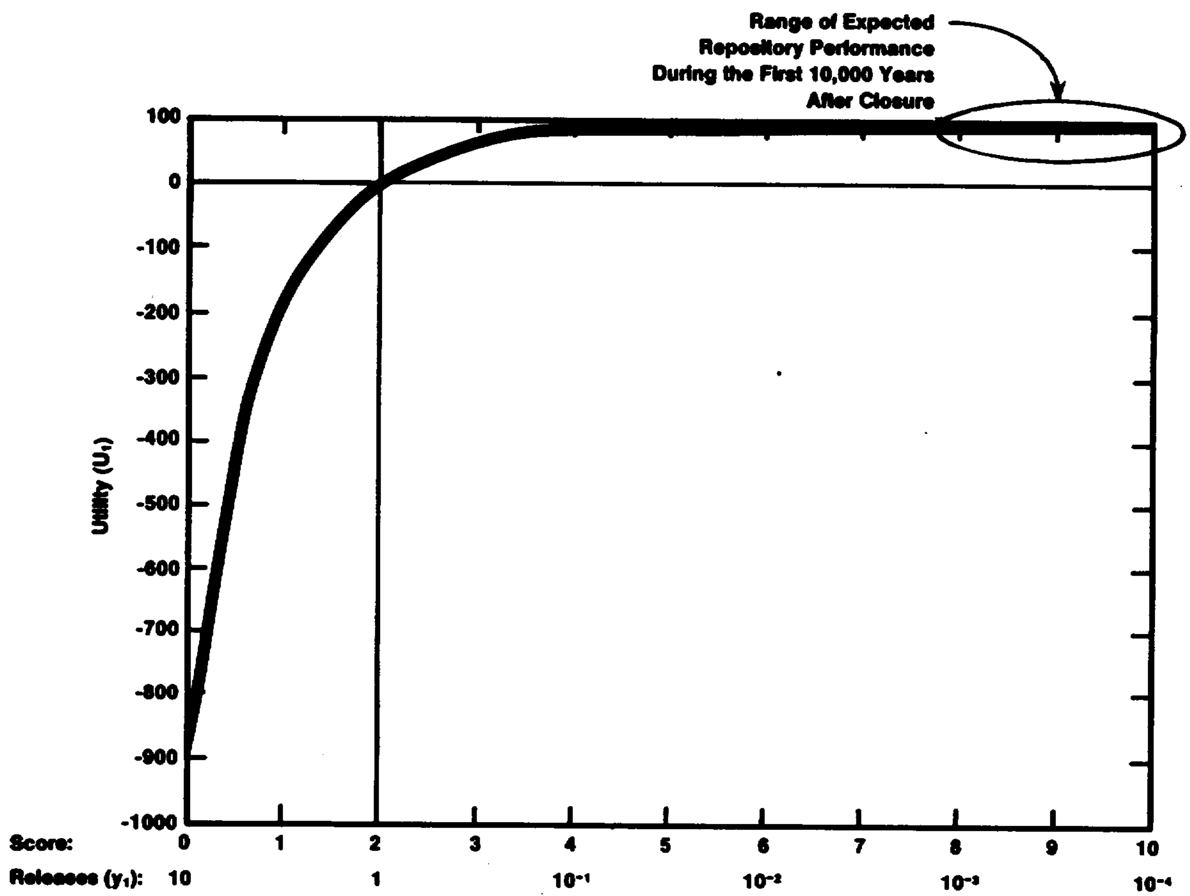

Figure 3-7. Utility plotted as a function of the score for the first 10,000 years after repository closure.

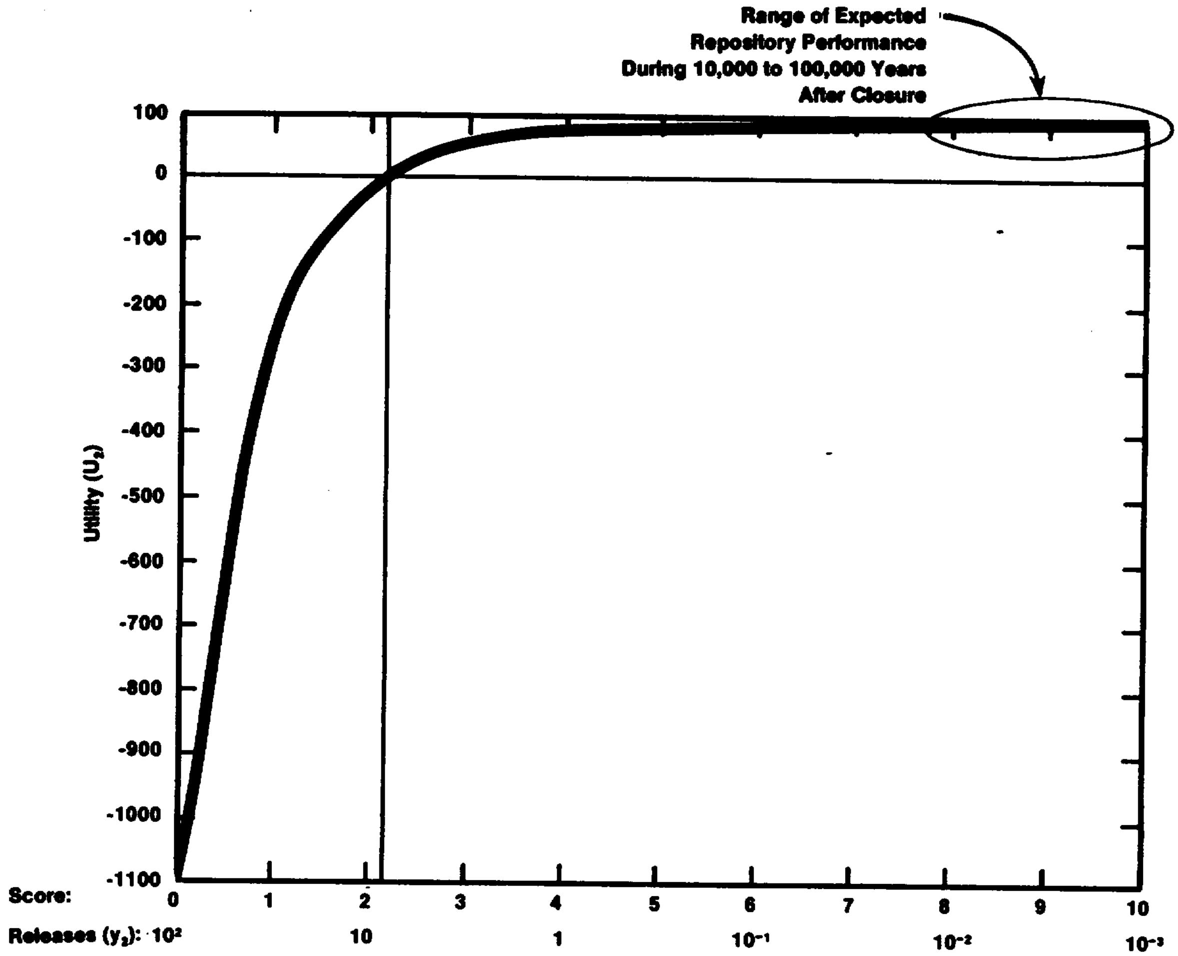

Figure 3-8. Utilities plotted as a function of score for the time period 10,000 to 100,000 years after closure.

As can be seen from Table 3-5, the policy judgment that the utility of postclosure performance in a given time period should be proportional to the cumulative releases during that time period has the effect of assigning a very high utility to any site receiving a score above 6. The reasoning underlying this judgment is that a site with releases that are 10,000 times lower than the EPA limits has little practical advantage over a site with releases that are 100 times lower. Although the use of a performance-measure scale that is geometric in releases allowed technical specialists the opportunity to make fine distinctions in the estimates of releases from repositories at the various sites, from a policymaking perspective these distinctions have little significance.

Table 3-5. Correspondence among scores, releases, and utilities

Score	Releases[a] (y_1, y_2)	Utility (U_1, U_2)
EARLY PERIOD: 0 to 10,000 YEARS AFTER CLOSURE		
--	0.0000	100.00
10	0.0001	99.99
9	0.0003	99.97
8	0.0010	99.90
7	0.0032	99.68
6	0.0100	99.00
5	0.0316	96.84
4	0.1000	90.00
3	0.3162	68.38
2	1.0000	0.00
1	3.1623	-216.23
0	10.0000	-900.00
LATE PERIOD: 10,000 to 100,000 YEARS AFTER CLOSURE		
--	0.0000	100.00
10	0.0010	99.99
9	0.0032	99.96
8	0.0100	99.89
7	0.0316	99.65
6	0.1000	98.89
5	0.3162	96.49
4	1.0000	88.89
3	3.1623	64.86
2.09	9.0000	0.00
2	10.0000	-11.11
1	31.6228	-251.36
0	100.0000	-1011.11

[a] Multiple of EPA limits for the first 10,000 years after repository closure.

3.5.2 ASSESSMENT OF SCALING FACTORS

The postclosure release estimates provide a measure of how well a repository at a given site is expected to perform under a given scenario in each of the time periods under consideration--the first 10,000 years and 10,000 to 100,000 years after closure. The utility functions translate the estimated releases into units of utility, or desirability. To obtain an overall measure of a site's postclosure utility, the various release estimates and utilities must be aggregated. The method of aggregation can be described in the following manner. Let $S_1, S_2, \ldots, S_m$ denote the scenarios to be considered at a given site. For a given scenario S_i, let $y_1(S_i)$ denote the estimated releases during the first 10,000 years. Similarly, let $y_2(S_i)$ be the releases estimated for 10,000 to 100,000 years after closure. Let $U_1[y_1(S_i)]$ and $U_2[y_2(S_i)]$ denote the utilities for the releases $y_1(S_i)$ and $y_2(S_i)$. The combined postclosure utility for a site given a scenario S_i is obtained from an equation of the form

$$U_{post}(S_i) = k_1U_1[y_1(S_i)] + k_2U_2[y_2(S_i)], \tag{3-3}$$

where k_1 and k_2 are scaling factors. The linear additive form, which involves weighting and adding the utilities for the two postclosure time periods, may be justified from independence arguments, as described in Appendix G.

The parameters k_1 and k_2 in Equation 3-3 are scaling factors that reflect the relative values of performance against the first and the second postclosure objectives. The numerical values of the parameters can be interpreted as follows. The parameter k_1 is the increase in the overall postclosure utility that would be achieved by decreasing releases in the first period enough to increase by one unit the utility on the first performance measure. According to Equation 3-1, a reduction in releases equal to 0.01 of the EPA release limits would increase the utility of performance in the first time period by one unit. Hence, k_1 is the increase in the overall postclosure utility of a site that would result if that site's releases during the first time period were reduced by 0.01 of the limits specified by the EPA standards. Similarly, k_2 is the increase in the overall postclosure utility that would be achieved by decreasing releases in the second period enough to increase by one unit the utility on the second performance measure. By Equation 3-2, k_2 is the increase in the overall postclosure utility of a site that would result if that site's releases during the second time period were reduced by 0.09 (0.01 in each 10,000-year interval) of the EPA limits.

To obtain a range of reasonable values for k_1 and k_2, the DOE managers (Table A-4) were asked to estimate societal preferences for hypothetical performance outcomes. The considerations involved hypothetical sites that would perform relatively well in one time period but poorly in the other. For example, one comparison involved the following performance outcomes for hypothetical sites A and B: At site A, the cumulative releases during the first 10,000 years are 10,000 times lower than the EPA limits (a score of 10 for this period). In the second period, however, the cumulative releases at site A were 100 times higher than the EPA limits (a score of 0). In contrast, at site B, the cumulative releases during the first 10,000 years were equal to 10 times the limits (a score of 0), but the cumulative releases during the second period were 1000 times lower than the limits (a score of 10). The table below summarizes the comparison (the releases are given as fractions of the EPA limits).

	Period 1		Period 2	
Site	Release	Score	Release	Score
A	0.0001	10	100	0
B	10	0	0.001	10

Three contrasting opinions were presented for which performance outcome--that associated with site A or B--would be preferable. With one view, site A is preferable because it performs extremely well during the first 10,000 years, the period that is emphasized in the regulations governing geologic disposal. According to another view, however, site B is preferable because the combined release from the two time periods is approximately only one-tenth as great

(10.001 times the limits versus 100.0001 times the limits). According to the third view, sites A and B are roughly equally desirable. One argument supporting this last view is that the rate of release per unit time in each of the time periods is approximately equal.

If the third view is taken (that the two sites are equally desirable), values for the scaling factors can be derived as follows: From Equation 3-3 and Table 3-5, the postclosure utility of site A is

$$U_{post}^{A} = k_1U_1(10^{-4}) + k_2U_2(100) = 99.99k_1 - 1011.11k_2.$$

Similarly, the postclosure utility of site B is

$$U_{post}^{B} = k_1U_1(10) + k_2U_2(10^{-3}) = -900.00k_1 + 99.99k_2.$$

Because indifference between the two cases implies equal utility,

$$99.99k_1 - 1011.11k_2 = -900.00k_1 + 99.99k_2,$$

which implies that

$$k_1 = 1.111k_2.$$

If the scaling factors are normalized to sum to unity,

$$k_1 + k_2 = 1,$$

then

$$k_1 = 0.526 \quad \text{and} \quad k_2 = 0.474.$$

After considerable discussion among the DOE managers, the above values were adopted as base-case values for the scaling factors. To accommodate the alternative views, however, more-extreme values were adopted to provide a range for sensitivity analyses. At one extreme, it was argued that all weight should be given to the first time period. Thus,

$$k_1 = 1.0 \quad \text{and} \quad k_2 = 0.0$$

were selected as one extreme for sensitivity analysis. At the other extreme, it was assumed that a given magnitude of cumulative releases during the second period was just as undesirable as the same magnitude of cumulative releases in the first period. With this view, the following hypothetical site outcomes (with releases stated as fractions of the EPA limits) would be judged equally desirable:

	Period 1		Period 2	
Site	Release	Score	Release	Score
C	0.001	8	10	2
D	10	0	0.001	10

The utilities of sites C and D are

$$U_{post}^{C} = k_1U_1(10^{-3}) + k_2U_2(10) = 99.90k_1 - 11.11k_2$$

and

$$U_{pos,t}^{D} = k_1U_1(10) + k_2U_2(10^{-3}) = -900.00k_1 + 99.99k_2.$$

Assuming indifference implies that the two utilities are equal, then

$$k_1 = 0.100 \quad \text{and} \quad k_2 = 0.900.$$

These values of k_1 and k_2 were used as the other extreme for sensitivity analyses.

3.5.3 SPECIFICATION OF THE MULTIATTRIBUTE UTILITY FUNCTION

According to the multiattribute utility theory, which is described in more detail in Appendix G, a measure of site desirability with respect to postclosure performance can be obtained by calculating the expected value of the postclosure utility, where utility is calculated from Equation 3-3. Mathematically, the expected utility can be expressed as

$$E(U_{post}) = p_1U_{post}(S_1) + p_2U_{post}(S_2) + \ldots + p_mU_{post}(S_m), \quad (3\text{-}4)$$

where U_{post} (S_i) is the postclosure utility of the site for scenario S_i (computed from Equation 3-3) and p_i is the probability assessed for scenario S_i for the given site (where $i = 1,2,\ldots,m$). Thus, the expected utility is obtained by weighting the postclosure utility of the site for each applicable scenario by the probability of the scenario and summing the results.

Equation 3-4 assumes a neutral attitude toward risk in the sense that the effect on the computed expected postclosure utility of a low-probability scenario is proportional to the product of the release and the probability of the scenario. However, many people are averse to risk: to avoid a possible loss, they would pay more than the probability times the magnitude of the loss (e.g., pay more than $5 to avoid a 5-percent chance of losing $100). Because of risk aversion, it is sometimes argued that low-probability scenarios with significant adverse consequences should be given greater emphasis than that provided by an expected-value calculation. It is possible to test whether the ranking of a set of options changes if a risk-averse, rather than a risk-neutral, attitude is assumed. The next section presents the numerical results of applying Equations 3-3 and 3-4 and includes tests of the sensitivity of these results to changes in attitudes toward risk, evaluations of site performance, and estimates of scenario probabilities.

3.6 RESULTS AND SENSITIVITY ANALYSIS

If the base-case probabilities in Table 3-3 are used for the appropriate scenarios and the base-case scores in Table 3-4 are used with Table 3-5 to estimate the releases that would occur for a given scenario, the expected releases for various time periods and the corresponding expected postclosure utilities for the sites are as given in Table 3-6. "Expected utilities" are the expected values of the utilities of the site. "Expected releases" are the expected values of releases; that is, the sum of the releases estimated for various scenarios, weighted by the probabilities of the scenarios. As indicated, all of the sites have very low expected releases and very high expected postclosure utilities. The Davis Canyon and the Richton Dome sites have the highest expected utility values of 99.99 and are ranked first. The Deaf Smith and the Yucca Mountain sites are only slightly lower at 99.98, and the Hanford site is the lowest, with an expected postclosure utility of 99.76.

These high expected utility values can be compared with the corresponding utilities that would be calculated for the hypothetical sites used as benchmarks in the scales of Figures 3-3 and 3-4. Suppose, for example, that a site with the characteristics given a score of 4 in Figure 3-3 and a score of 4 in Figure 3-4 was evaluated. The computed base-case postclosure utility for that site would be 89.47. More generally, sites whose scores for the first and the second postclosure time periods (10,000 years and 10,000 to 100,000 years) are 10 and 10, 8 and 8, 6 and 6, 4 and 4, 2 and 2, and 0 and 0 would have base-case postclosure utilities of 100, 99.90, 98.95, 89.47, -5.27, and -952, respectively. Only the sites with the lowest pairs of scores, 0 and 0 as well as 2 and 2, would receive low postclosure utilities. This is because it is judged that only under these relatively poor site conditions are significant releases likely.

The differences in the computed base-case expected postclosure utilities can be traced to the different scenario probabilities and scores assigned in Tables 3-3 and 3-4. Because scenario 1 (the nominal case) is by far the most likely for each site, its scores have a dominant effect on the expected postclosure utilities. The ranking of the sites, in fact, exactly matches the order of the base-case scores assigned for this scenario. Scenario 2 (unexpected features) also has a significant effect because of its relatively high probability in comparison with the other scenarios. Because the base-case scores for scenario 2 are closely correlated with the base-case scores for scenario 1, the effect of the second scenario is to reinforce the differences in the expected performances estimated for the sites in the nominal case.

The expected postclosure utilities can be interpreted by recalling the relationship between the individual utilities for each postclosure period and the releases that occur during that period (Table 3-5). The fact that the Davis Canyon and the Richton Dome sites were computed to have expected postclosure utilities of 99.99 implies that these sites were judged essentially equal to a site whose cumulative releases are approximately 0.00011 of the EPA limits during each 10,000-year interval after repository closure for 100,000 years. The expected utilities for the Deaf Smith and the Yucca Mountain sites are only slightly lower. The computed utilities indicate a judgment that these sites are comparable to a site with releases approximately twice that given above (about 0.00023 of the EPA limits). The computed postclosure utility of 99.76 for the Hanford site indicates that it is estimated to be equal to a site with releases approximately 22 times higher (about 0.0024 of the EPA limits) than that given in the first instance above. The uniform releases per 10,000-year interval that would be assigned a utility equal to the expected utility for each site are called "equivalent releases" and are shown in Table 3-6. The utilities computed for the various sites are extremely high (close to 100) because the equivalent releases are only a small fraction of the EPA release limits.

Table 3-6. Computed base-case expected releases and postclosure utilities[A]

Site	Expected releases: 0-10,000 years[B]	Expected releases: 10,000-100,000 years[B]	Expected releases: 0-100,000 years[B]	Expected postclosure utility	Equivalent release per 10,000 years[A,B]
Davis Canyon	1.03×10^{-4}	1.03×10^{-3}	1.13×10^{-3}	99.99	1.09×10^{-4}
Deaf Smith	1.15×10^{-4}	3.26×10^{-3}	3.38×10^{-3}	99.98	2.33×10^{-4}
Richton Dome	1.04×10^{-4}	1.04×10^{-3}	1.15×10^{-3}	99.99	1.10×10^{-4}
Hanford	1.25×10^{-3}	3.32×10^{-2}	3.44×10^{-2}	99.76	2.41×10^{-3}
Yucca Mountain	1.17×10^{-4}	3.29×10^{-3}	3.40×10^{-3}	99.98	2.35×10^{-4}

[A] See text for explanation.
[B] Fraction of EPA limits for the first 10,000 years after repository closure.

Some indication of whether the differences in expected postclosure utilities are significant in relation to existing uncertainties can be found by exploring the sensitivity of the results to various assumptions. Sensitivity analyses are performed to determine (1) which parameters of the expected-utility equations (i.e., Equations 3-3 and 3-4) have the greatest effect on the expected utilities and rankings of the five nominated sites and (2) which parameters, when varied across their ranges of uncertainty, cause the base-case ranking of sites to change, thus indicating which assumptions or values could affect the ranking of the sites.

The key results of the various sensitivity analyses are shown in the figures to be presented in this section. Most of the figures show how various assumptions affect the expected postclosure utility for each site and the equivalent releases (releases per 10,000 years that would cause a site to have a utility just equal to the expected utility). In general, the sensitivity analyses indicate that the base-case ranking of the sites is robust in the sense of being relatively insensitive to uncertainties or value assumptions.

Figures 3-9, 3-10, and 3-11 show how the expected postclosure utilities for each site depend on basic uncertainties and value assumptions. Figure 3-9 shows the range of expected postclosure utilities as the scores for each site are simultaneously varied from the high to the low estimates in Table 3-4 with the probabilities of scenarios kept at the base-case estimates. Figure 3-10 shows the range of the expected postclosure utilities as the probabilities of disruptive and unexpected-feature scenarios are simultaneously varied from the high to the low estimates given in Table 3-3 with the scores kept at base-case values. Figure 3-11 shows the range of the expected postclosure utilities as scores and probabilities are simultaneously varied from optimistic assumptions (high scores for the sites and low probabilities for disruptive and unexpected-feature scenarios) to pessimistic assumptions (low scores for the sites and high probabilities for disruptive and unexpected-feature scenarios).

Figure 3-12 shows the effect of assuming increasing aversion to risk. To obtain these results, possible outcomes involving high releases were given greater weight through the use of an exponential function whose effect is determined by a parameter called the "risk-preference constant." Chapter 4 describes the method in more detail. When the constant is set to zero, no risk aversion is assumed, and the results are identical with the expected-value calculation. Decreasing the value for the coefficient below zero adjusts the utilities to account for greater aversions to the possibilities involving high releases. Because the base-case release estimates are low even for the scenarios involving unexpected features and disruptive processes and events, risk aversion does not significantly alter the relative utilities or change the site rankings. With high levels of risk aversion, Yucca Mountain is slightly less preferred because of the possibility of relatively high releases under the low-probability scenarios involving extrusive magmatic events. The y-axis in the figure is expressed in terms of equivalent releases.

Figure 3-13 shows the effect of changing the assumption that the single-attribute utility functions are linear in cumulative releases. The effect is to intensify (or reduce) the impact of scenarios, but the ranking of sites is not changed. Thus, if the utility function is curved in such a way that the marginal value of reducing releases is greater when releases are low than it is when they are high, the sites with smaller nominal releases attain more-favorable expected utilities. Sensitivity analysis shows that the effects of such curvatures on expected utilities are extremely small.

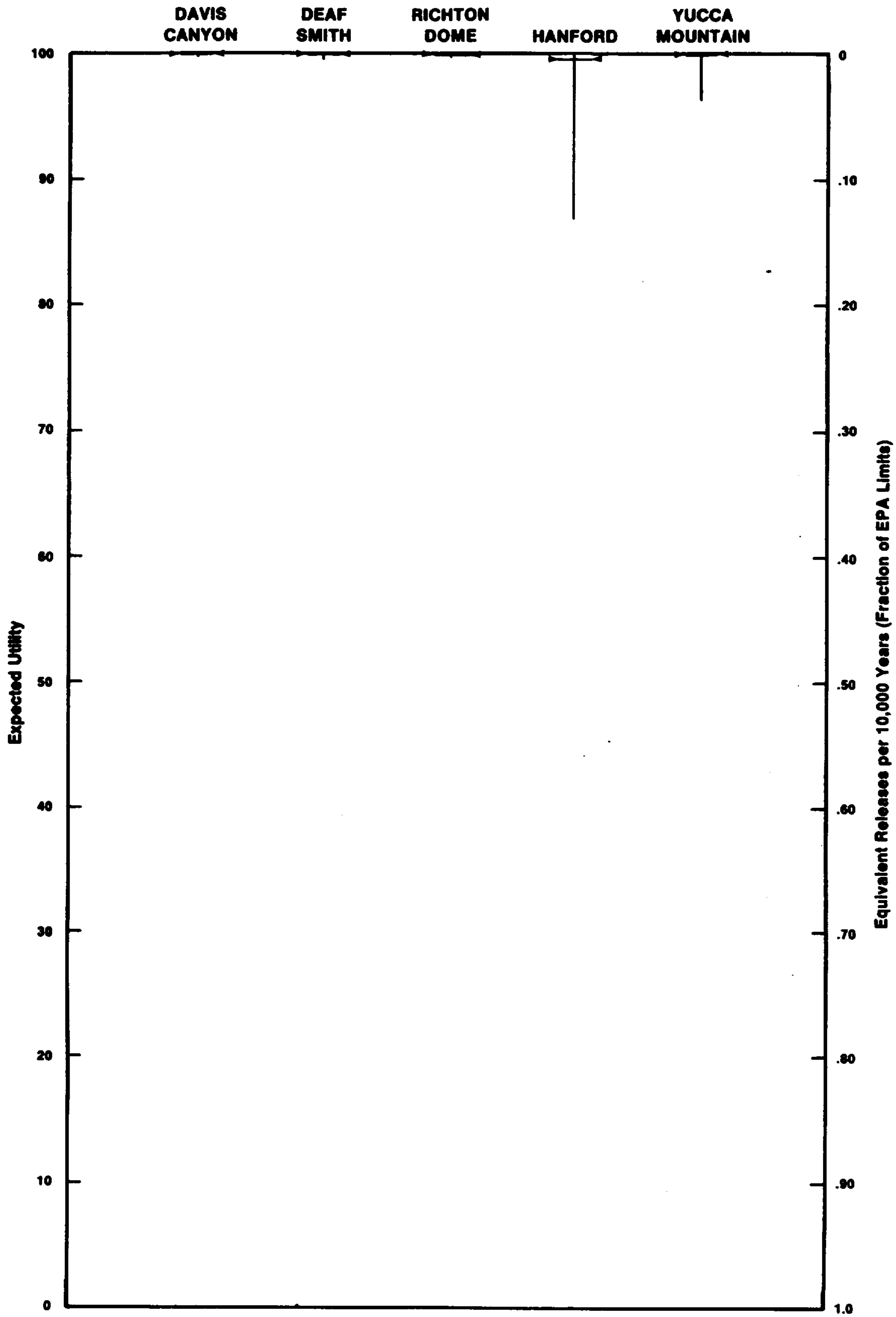

Figure 3-9. Sensitivity of the expected postclosure utility and the equivalent releases to variations in site scores from high to low judgmental estimates. Arrowheads indicate the base-case expected utilities.

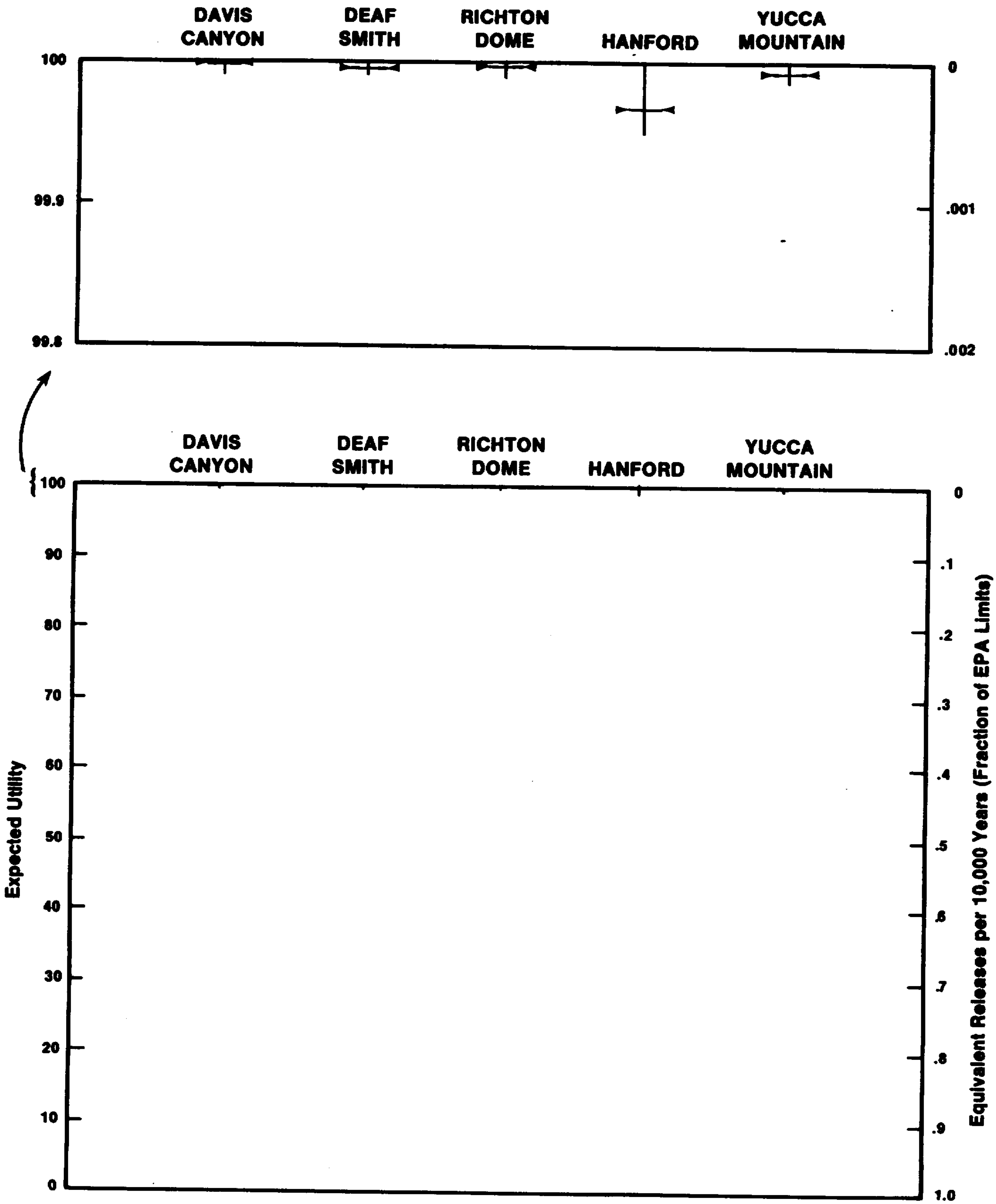

Figure 3-10. Sensitivity of the expected postclosure utility and the equivalent releases to variations in scenario probabilities for the sites. The figure at the top shows an enlargement of the extreme top of the scale (99.8 to 100). Arrowheads indicate the base-case expected utilities.

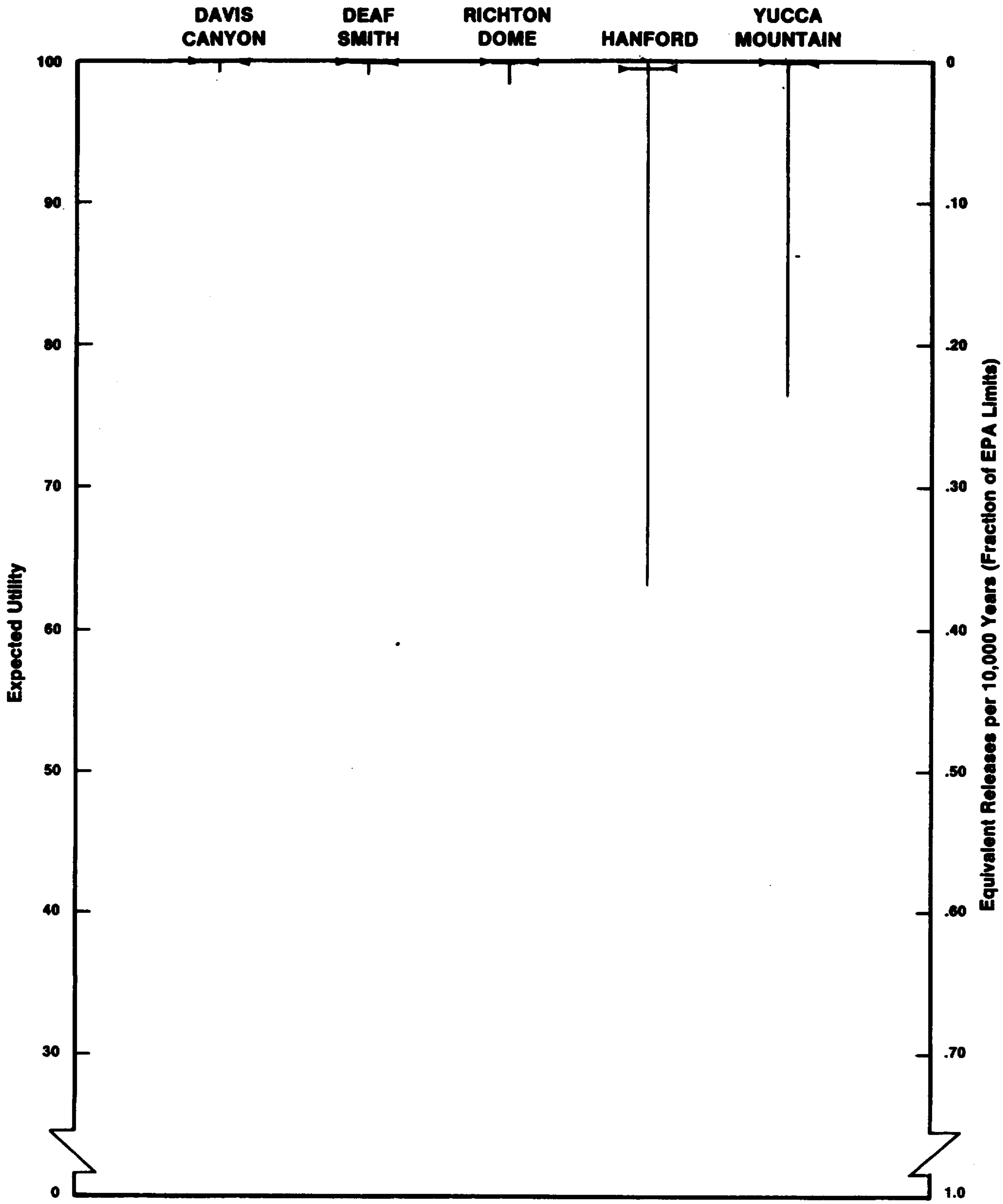

Figure 3-11. Sensitivity of the expected postclosure utility and the equivalent releases to variations in scores and scenario probabilities from optimistic (high scores and low probabilities for disruptive and unexpected-feature scenarios) to pessimistic (low scores and high probabilities for disruptive and unexpected-feature scenarios). Arrowheads indicate the base-case expected utilities.

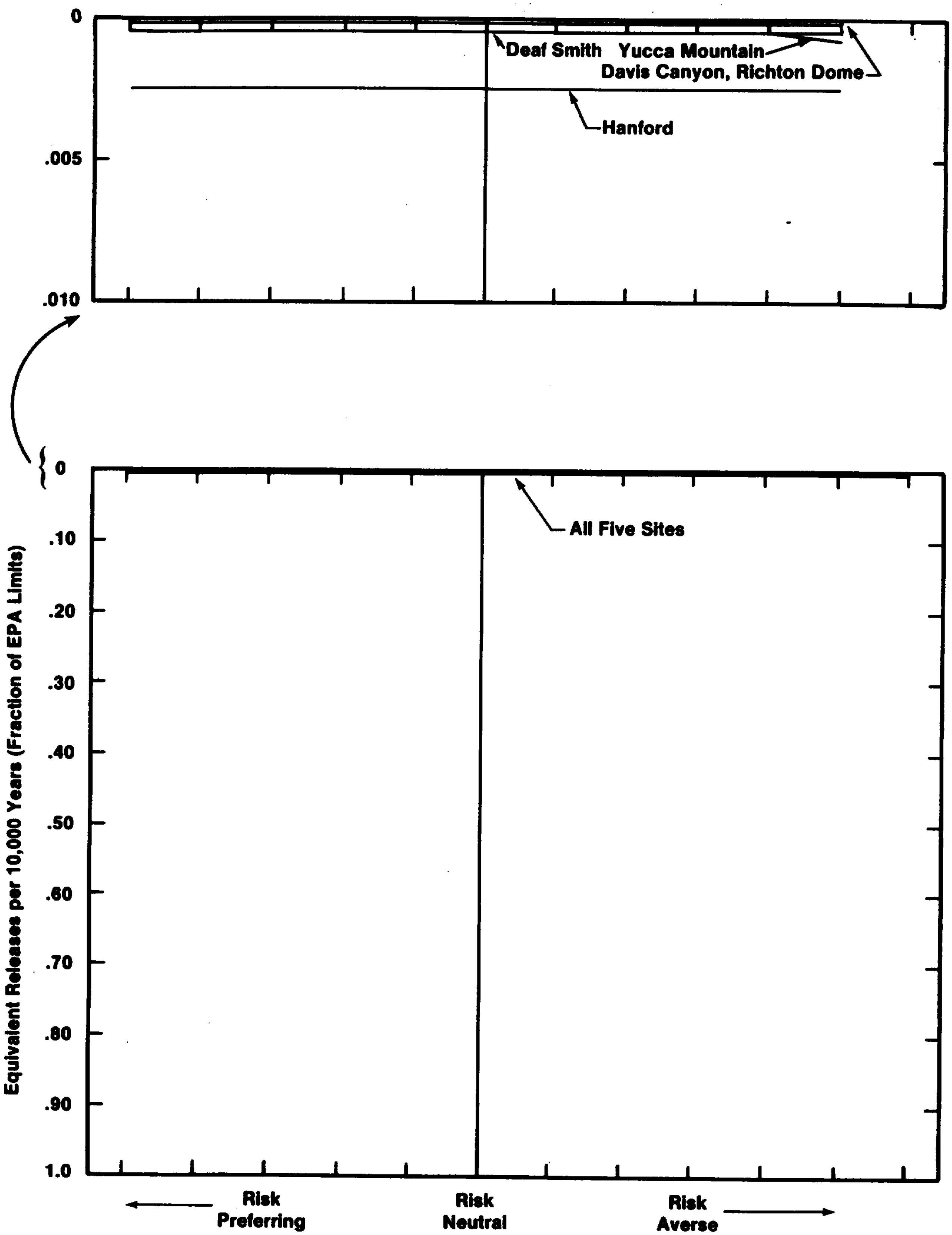

Figure 3-12. Sensitivity of postclosure certain-equivalent releases to risk attitude. The figure at the top shows an enlargement of the extreme top of the scale (0.010 to 0).

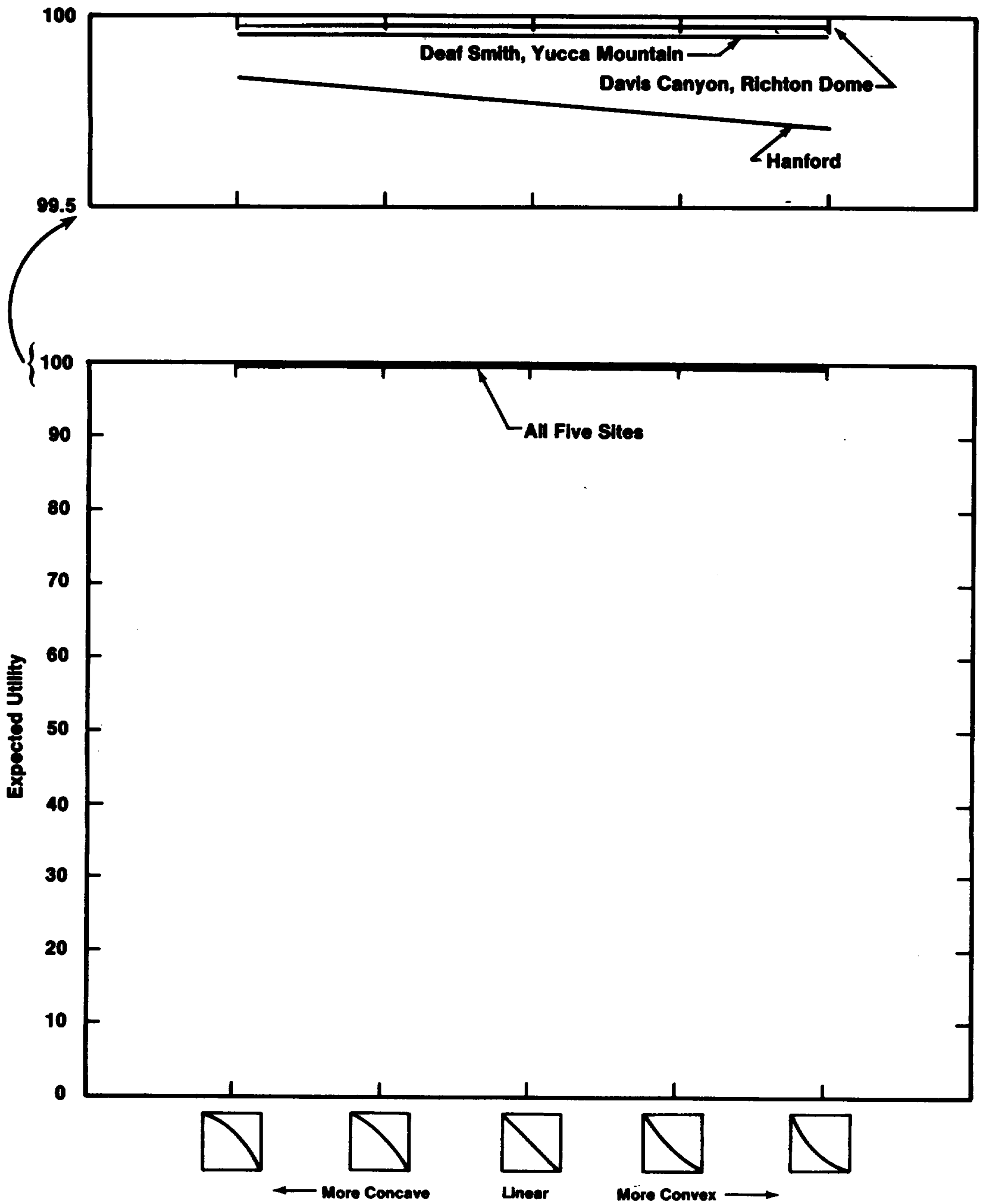

Figure 3-13. Sensitivity of the expected postclosure utility and the equivalent releases to variations in assumptions about the curvature of the single-attribute utility function. The figure at the top shows an enlargement of the extreme top of the scale (99.5 to 100).

As explained in Section 3.3.1, scenarios involving disruptive processes and events considered only the processes or events that might occur during the first 10,000 years after repository closure. To check the effect of relaxing this assumption, the expected postclosure utilities of the sites were recomputed with the probabilities of disruptive scenarios increased by a factor of 10. Such an assumption would tend to overestimate the effects of disruptive processes and events that might occur during the first 100,000 years because, although this period is 10 times as long, disruptions occurring 10,000 to 100,000 years after closure are unlikely to produce cumulative releases as large as they would if they were to occur in the first 10,000 years. The results, shown in Figure 3-14, thus provide a conservative estimate of the effect of disruptions beyond the first 10,000 years. As indicated, there is little effect on the expected postclosure utilities.

The scaling constants k_1 and k_2 for early and late releases, respectively, reflect a value judgment about the relative importance of early and late releases. As shown by Figure 3-15, the Davis Canyon and the Richton Dome sites are not significantly affected by the values of the scaling constants, since estimated releases per 10,000-year interval are approximately constant. The Deaf Smith and the Yucca Mountain sites are slightly affected, and the Hanford site is more strongly affected. As the scaling factors are changed to increase the importance of later releases (i.e., from $k_1 = 1$ and $k_2 = 0$ to $k_1 = 0.1$ and $k_2 = 0.9$), the latter three sites decrease in expected utility. However, the rankings do not change, and the relative differences between the sites are not significantly affected. The magnitudes of the effects are much less than that produced by varying the probabilities of scenarios or the scores for the sites.

As explained in Section 3.4.1, the releases from a repository at various sites were estimated with the aid of constructed scales (Figures 3-3 and 3-4). These scales establish a correspondence between the hydrologic, geochemical, and geomechanical characteristics of a site and the radionuclide releases. As noted in the discussion of these scales, the releases corresponding to any given set of site characteristics could be 10 times higher or lower than the estimates given in the scales. Figure 3-16 shows the effect on the expected utility for each site as the releases are varied by a factor of 10 above and below the levels shown in Figures 3-3 and 3-4. Although the differences in expected utilities change, the ranking of the sites does not change.

The sensitivity results suggest that the most critical uncertainty for the calculation of the expected postclosure utilities of the sites is uncertainty in the scores assigned to represent the releases from the sites under various scenarios. As can be seen by comparing Figures 3-9 and 3-11, the effect is compounded by uncertainty over the appropriate judgmental probabilities for the unexpected-feature and disruptive scenarios.

To obtain a clearer understanding of the impact of the uncertainty on site scores and scenario probabilities on postclosure performance, an approximate analysis was conducted to estimate the full range of possible releases that might occur at each site, taking into account uncertainty in scores and scenario probabilities. Figure 3-17 shows the estimated ranges within which the releases at, and the corresponding utilities of, each site are likely to fall. Although Figure 3-17 appears similar to the earlier figures, the bars

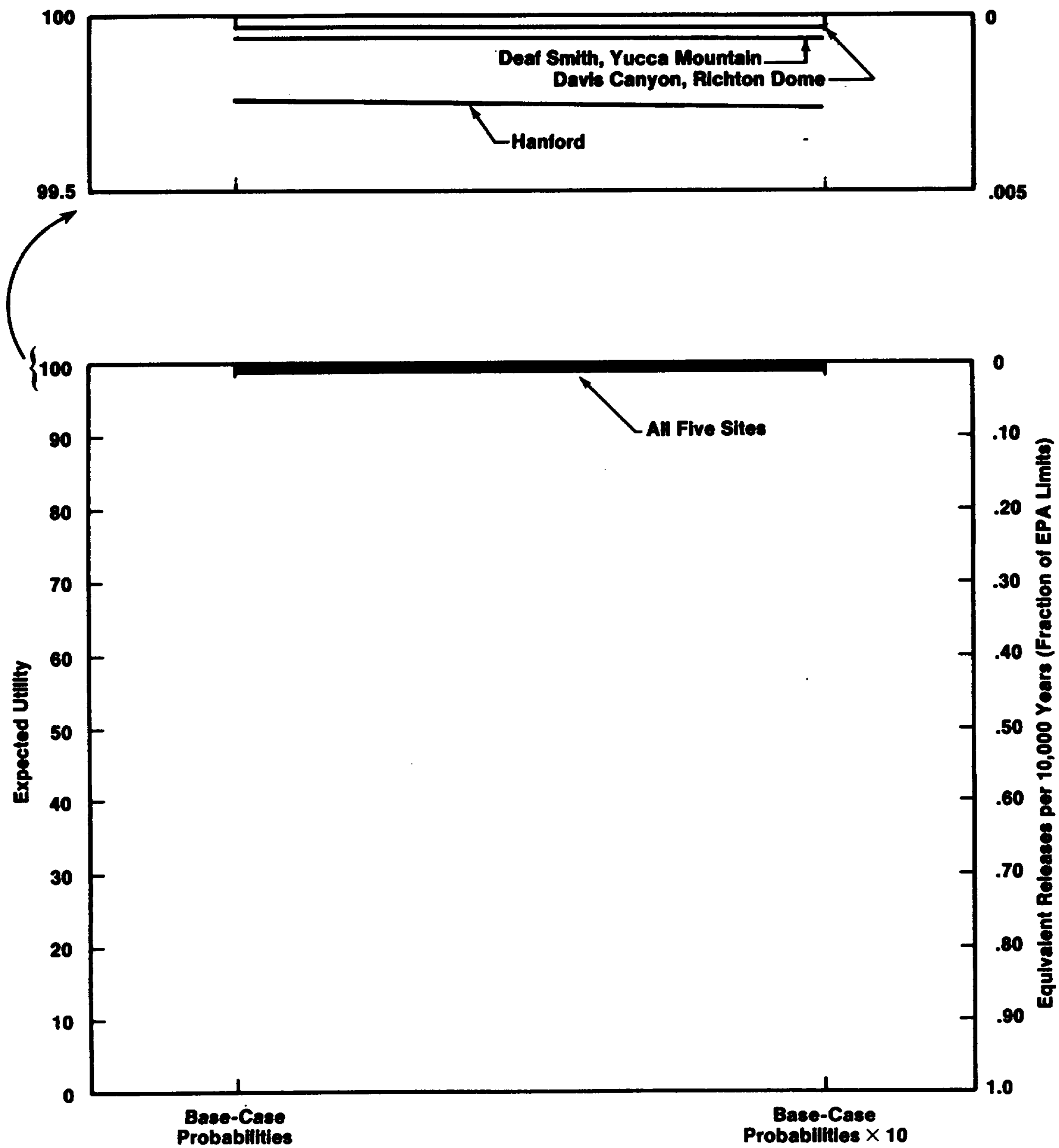

Figure 3-14. Sensitivity of the expected postclosure utility and the equivalent releases to scaling the probabilities of disruptive scenarios. The figure at the top shows an enlargement of the extreme top of the scale (99.5 to 100).

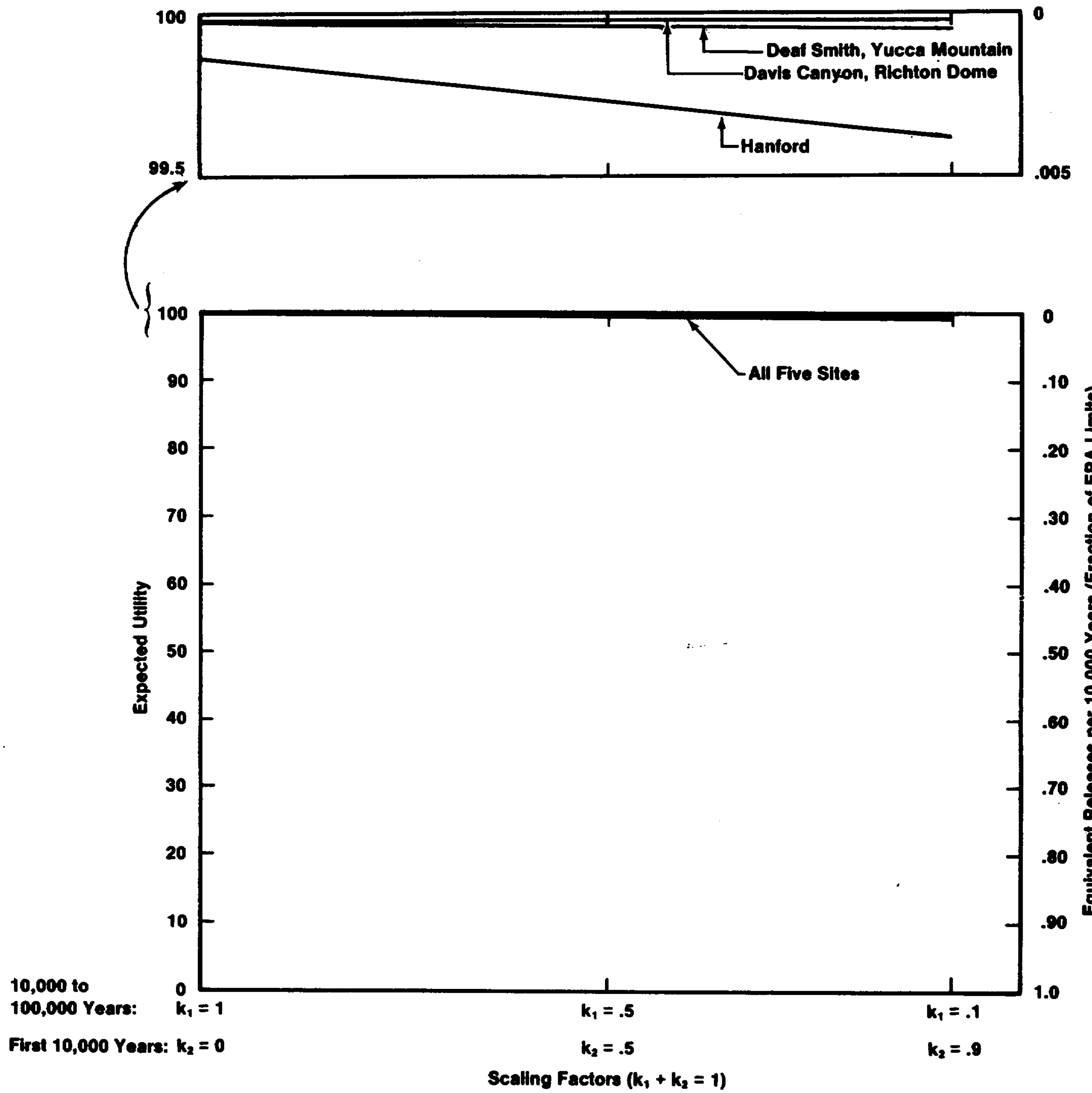

Figure 3-15. Sensitivity of the expected postclosure utility and the equivalent releases to variations in the values of the scaling factors. The figure at the top shows an enlargement of the extreme top of the scale (99.5 to 100).

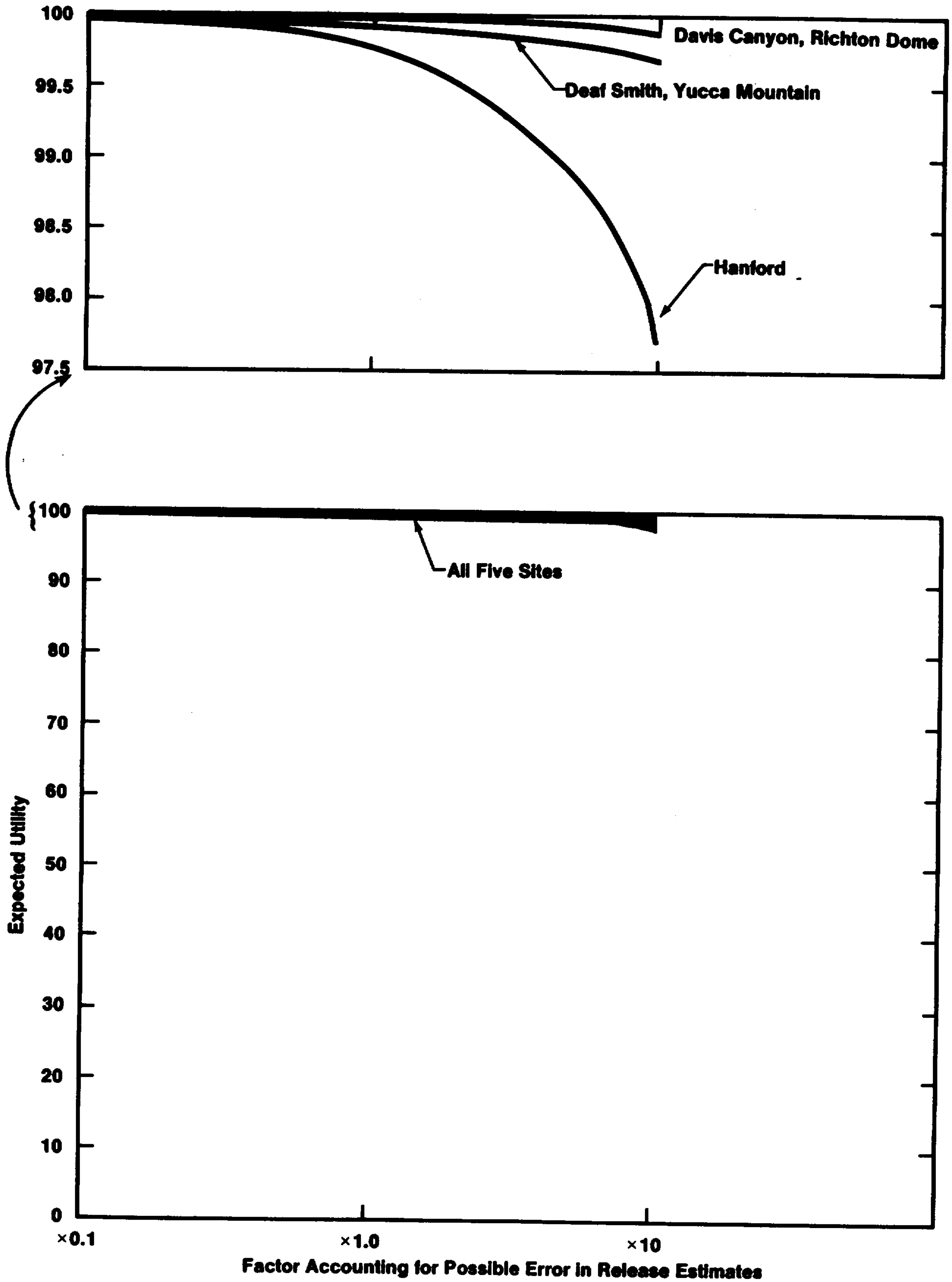

Figure 3-16. Sensitivity of the expected postclosure utility to uncertainty in correspondence between site characteristics and releases for the first 10,000 years and for the period 10,000 to 100,000 years. The figure at the top shows an enlargement of the extreme top of the scale (97.5 to 100).

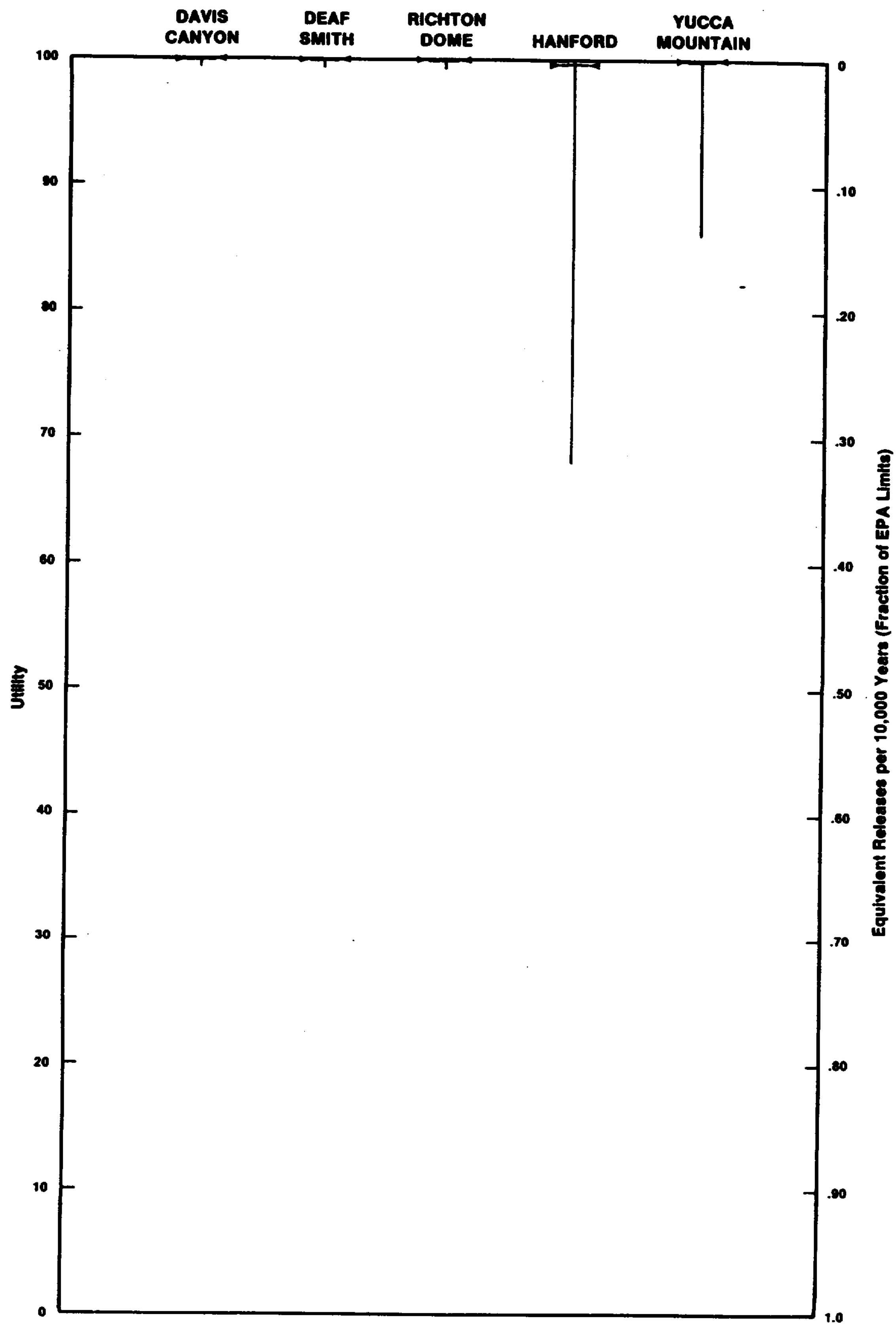

Figure 3-17. Ranges illustrating uncertainty in postclosure utilities and releases. Arrowheads indicate the base-case expected utilities. This figure should be considered together with Figure 3-18, which shows the relative likelihood of utility within a range of uncertainty.

indicate the likely range of actual utilities that might occur, rather than expected utilities wherein the low utility associated with each disruptive scenario is weighted by the low probability of the scenario's occurrence.

The approximate analysis that produced the results of Figure 3-17 consisted of the following steps. High, base-case, and low scores were assumed to have probabilities of .13, .74, and .13, respectively, for each site and scenario. These probabilities provide a more accurate discrete approximation to the uncertainty over scores (i.e., they more accurately approximate the variance) than probabilities of .05, .09, and .05, assuming that the continuous probability distributions on scores are bell-shaped. Similarly, probabilities of .13, .74, and .13 were assigned to each of the high-probability, base-case, and low-probability estimates for each scenario. The releases associated with the various combinations of scores were then evaluated, and each release was assigned a probability, assuming the independence of all probabilities.

The ranges shown in Figure 3-17 can be interpreted as approximate 98-percent confidence bands, derived according to the above assumptions. They encompass all but the highest and the lowest computed results, each of which accounts for 1 percent of the total probability. Although the uncertainty in the postclosure performance of the nominated sites is such that any of the utilities within the ranges are possible, outcomes near the high end of the ranges are much more likely. Figure 3-18 illustrates the general shape of the probability density functions that describe the relative likelihoods of various postclosure utilities. (The curve has been smoothed to eliminate discontinuities produced by the discrete approximation.) Because of the approximations and questionable assumptions underlying Figure 3-17 and 3-18 (especially independence), the numerical results should not be taken literally. Nevertheless, they strongly suggest that sites with a lower expected postclosure utility also tend to have greater uncertainty in postclosure performance.

3.7 CONCLUSIONS FROM THE POSTCLOSURE ANALYSIS

A number of conclusions can be derived from the base-case expected utilities, the ranges of uncertainty in releases, and the sensitivity analysis. Most striking is that all of the sites are expected to perform extremely well and are capable of providing exceptionally good waste isolation for at least 100,000 years after repository closure. As already mentioned, this finding is consistent with other studies of expected repository performance at carefully screened sites. When placed on a scale where a 0 can be interpreted as performance at the minimum level required by the primary-containment requirements of the EPA standards and 100 is perfection, all of the sites have expected utilities of 99.7 or higher. This corresponds to an assessment that all of the sites are as desirable as a site with an average release rate that is less than 0.003 of the EPA limits for 10,000 years.

The analysis shows that, under some unlikely disruptive scenarios and pessimistic assumptions, it is possible for a site to have releases that are a significant fraction of the EPA limits. At the salt sites, releases could be as high as one-tenth or so of the limits; at the nonsalt sites, releases could

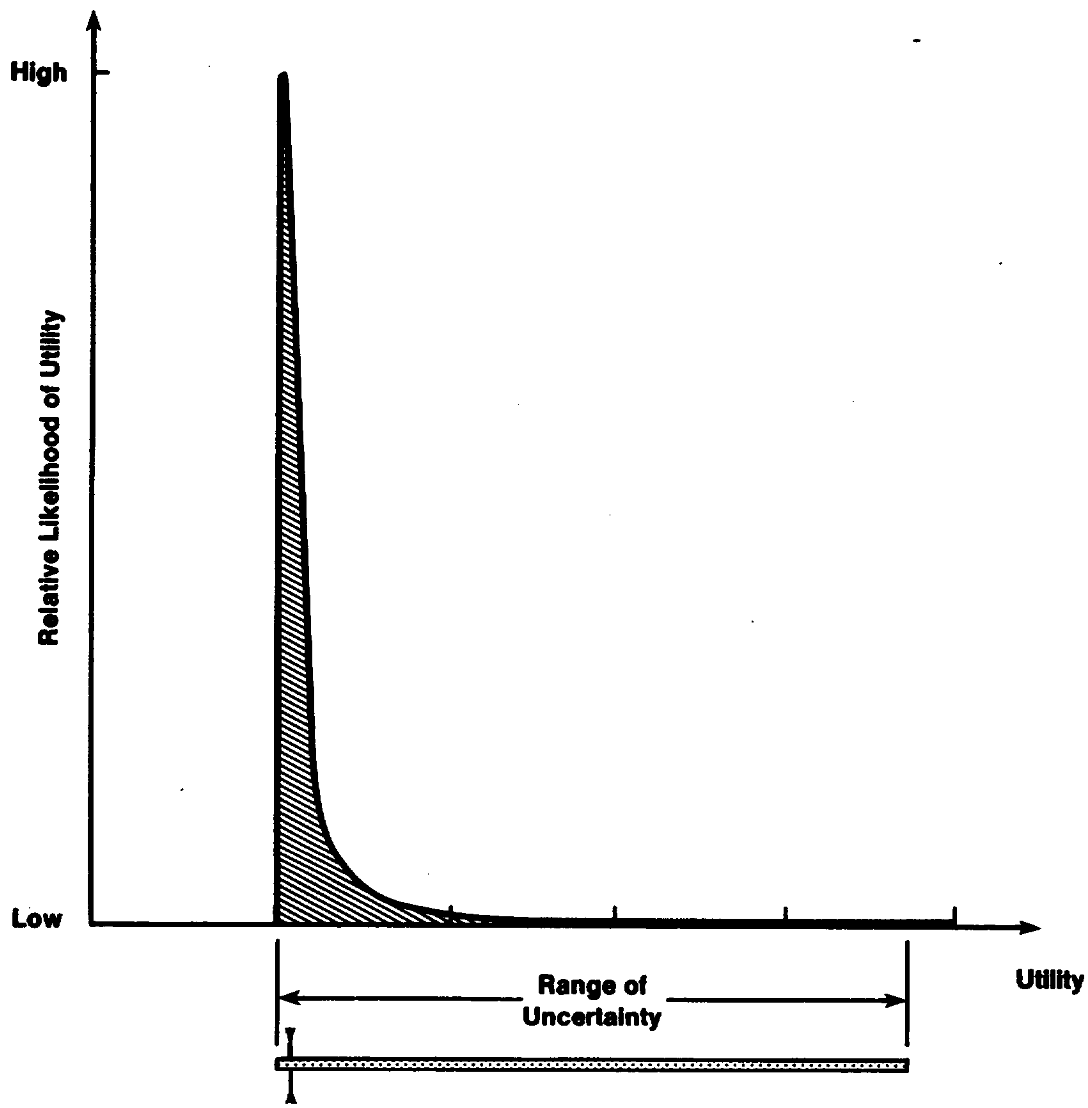

Figure 3-18. Approximate relative likelihood of achieving any given utility within a specified range of uncertainty (see Figure 3-17). Small arrowheads on the bottom bar indicate the base-case expected utility.

be equal to or greater than the limits. However, the probabilities of scenarios producing these higher releases are judged to be extremely low, only a few chances in a thousand at most.

From the relative ranking of the sites and estimates of uncertainty, it appears that the postclosure performance of a repository at the Hanford site would be slightly less favorable than that of a repository at the salt sites or at the Yucca Mountain site. The principal bases for this conclusion are technical judgments regarding the potential for waste dissolution, radionuclide travel time, and the possibility of the existence of unexpected features at the site. It must be kept in mind, however, that the release estimates are very low, and the utility differences among the sites are extremely small. The probabilities of the various possible postclosure releases and utilities (Figures 3-17 and 3-18) indicate that there is about one chance in five to one chance in ten that a repository at the Hanford site would actually have a lower level of releases than a repository at any of the salt sites.

Thus, there is greater confidence in the salt sites than in the nonsalt sites, and there is more confidence in the Yucca Mountain site than in the Hanford site. This is because of greater uncertainty in the performance of the nonsalt sites (especially the Hanford site) under expected conditions and a higher probability of significant disruptive scenarios and unexpected features at the nonsalt sites. Despite these differences, however, it is clear that the confidence in all sites is extremely high.

The postclosure rankings produced by the analysis are relatively insensitive to variations in assumptions, the uncertainty represented by the range of release estimates, and alternative value judgments. The differences in the expected postclosure utilities estimated for the sites, which quantify the relative postclosure desirabilities of the sites, are extremely small. Uncertainties not accounted for in the analysis, such as errors associated with the limits of human judgments or the possibility of unidentified mechanisms for releases, may be greater than the small postclosure differences identified by the analysis.

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Chapter 4

PRECLOSURE ANALYSIS OF THE NOMINATED SITES

This chapter presents a preclosure analysis of the five sites nominated as suitable for characterization. Section 4.1 presents the objectives defined for the evaluation of the sites. Section 4.2 defines a performance measure for each objective to indicate the degree to which the five sites achieve the objectives. Section 4.3 describes the performance of each site in terms of a set of performance measures. Section 4.4 discusses the multiattribute utility function assessed to integrate the ratings on the different performance measures into an overall evaluation of the sites. The results of the base-case evaluation and numerous sensitivity analyses are presented in Sections 4.5 and 4.6, respectively. Section 4.7 discusses the conclusions of the preclosure analysis of sites.

4.1 THE OBJECTIVES HIERARCHY

The perspective taken in this analysis is that the sites should be evaluated in terms of minimizing adverse preclosure impacts. This requires a set of objectives that characterize in a useful way the meaning of "adverse preclosure impacts." Specifically, the preclosure guidelines of 10 CFR 960.5 (DOE, 1984) specify the factors to be considered in evaluating and comparing sites on the basis of expected repository performance before closure. The preclosure guidelines specify three categories of factors: radiological safety; environment, socioeconomics, and transportation; and ease and cost of siting, construction, operation, and closure.

The preclosure guidelines were used as the basis for constructing the set of objectives represented by the objectives hierarchy in Figure 4-1. A combination of a top-down and bottom-up approach was used to develop the objectives hierarchy. In the top-down approach, the methodology lead group formulated an initial set of the most general objectives bearing on the ranking of the sites for the site-characterization decision. These general objectives, which were reviewed by members of DOE management and staff (see Appendix A), pertained to health and safety, environmental quality, socioeconomics, and costs. The general objectives were then made more specific by establishing what was meant by each, why it was important, how it might be affected by site selection, and so forth. As suggested in the professional literature, criteria of completeness, nonredundancy, significance, operationality, and decomposability were then applied to refine and improve the specification of lower-level objectives. The bottom-up approach involved working with the technical specialists (identified in Appendix A) to generate lists of objectives based on the siting guidelines and the "Supplementary Information" and Appendix IV to the guidelines. The identified objectives were then integrated into the objectives hierarchy developed from the top-down approach and approved by DOE management as the objectives of the preclosure analysis.

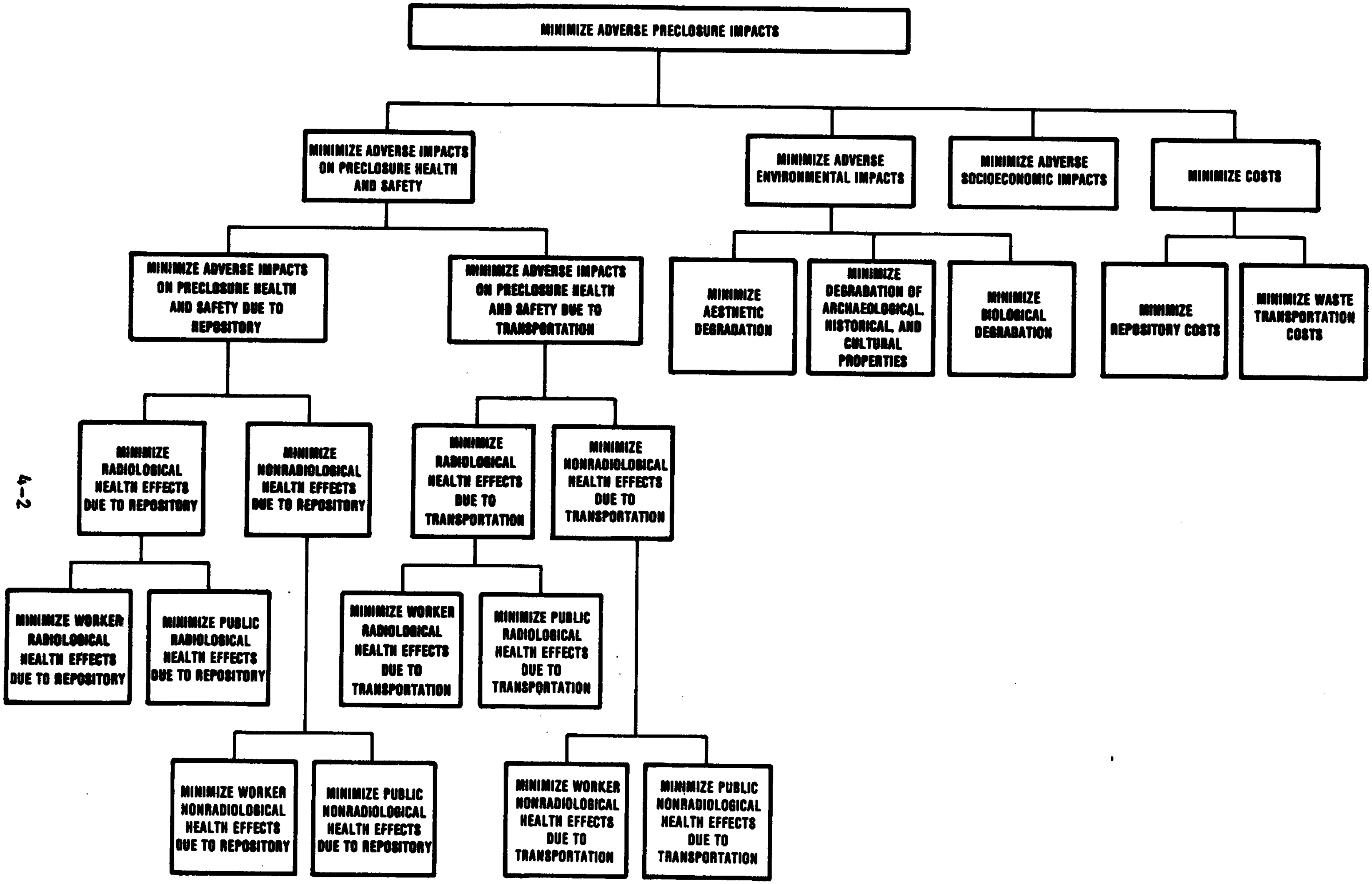

Figure 4-1. Preclosure objectives hierarchy.

As is readily evident, the minimization of preclosure impacts is defined to be equivalent to achieving to the extent practicable the following four major objectives:

- Minimize adverse impacts on health and safety before closure.
- Minimize adverse environmental impacts.
- Minimize adverse socioeconomic impacts.
- Minimize costs.

The meanings of each of these major objectives are made more precise by subobjectives and by the definition of the performance measures in Section 4.2.

Regarding preclosure health and safety, the possible impacts may be attributable to the repository itself or to waste transportation, they may be due to radionuclide releases or to nonradiological accidents and hazards, and they may be experienced by the public or by workers at the repository or in transportation. Thus, as shown in Figure 4-1, there are eight lowest-level objectives that correspond to the objective of minimizing adverse effects on preclosure health and safety. They range from minimizing the radiological health effects incurred by the public from the repository to minimizing the nonradiological health effects incurred by workers from waste transportation.

The environmental objective is divided into three more-specific subobjectives: to minimize adverse aesthetic impacts; to minimize adverse archaeological, historical, and cultural impacts; and to minimize adverse biological impacts. It is useful to recognize that objectives like "minimize air pollution" and "minimize the degradation of water resources," though important, are not explicitly included in the objectives hierarchy, because they are a means to achieving the fundamental objectives of the hierarchy. For instance, air pollution is a cause of nonradiological health effects in both the public and in workers, a cause of aesthetic degradation in rural areas, and a cause of biological impacts.

The socioeconomic objective is concerned with adverse impacts on the local communities surrounding a repository and disturbances of the lifestyles of their residents. These disturbances might be due, for example, to the influx of new residents or the use of local water resources.

The cost objective is divided into two subobjectives: to minimize the costs of the repository itself and to minimize the costs of waste transportation. As stated in the Nuclear Waste Policy Act, these costs are to be borne by the generators and owners of the waste.

4.2 PERFORMANCE MEASURES

For each of the lowest-level objectives in Figure 4-1, it is necessary to define a performance measure to indicate the degree to which the objective is achieved. For each site, repository performance before closure is then described in terms of impact levels for each performance measure. For example, the performance measure for the objective of minimizing repository costs is millions of dollars. The impact level for a given site might then be 8500 million dollars (i.e., 8.5 billion dollars). Collectively, the two cost impact levels indicate how well the overall cost objective is met. Similarly, the eight health-and-safety impacts collectively describe the degree to which each site meets the objective of minimizing adverse impacts on health and safety. Three impact levels are necessary to describe the environmental degradation for each site, and one level is used for adverse socioeconomic impacts.

As noted in Chapter 3, performance measures may involve scales of two different types: natural scales and constructed scales. Natural scales are those that have been established and enjoy common usage and interpretation; examples are costs in millions of dollars and numbers of fatalities. Constructed scales, on the other hand, are developed specifically for the problem. For instance, there is no natural scale for the objective "minimize aesthetic degradation." Hence, it is necessary to construct a scale that describes possible impacts. As will be readily apparent, health-and-safety objectives and cost objectives are measured by natural scales, whereas environmental and socioeconomic objectives are measured by constructed scales.

A listing of the 14 preclosure objectives and the associated performance measures is given in Table 4-1. For convenience in future reference, the performance measures are designated X_1 through X_{14} in the table.

4.2.1 PERFORMANCE MEASURES FOR HEALTH AND SAFETY

The eight performance measures for health and safety are the number of fatalities that might be attributed to the category characterized by the corresponding objective. For instance, with regard to the first objective of minimizing worker health effects due to radiation exposures at the repository, the performance measure is the number of cancer fatalities incurred by workers from radiation exposure at the repository.

All of the health-and-safety performance measures that are related to radiation exposure are numbers of cancer fatalities. The performance measures for nonradiological health-and-safety objectives are numbers of fatalities from accidents and possibly air pollution. (Air pollution is included mainly for completeness, as it is not expected to cause any fatalities.) The main reason for the nonradiological fatalities experienced by both workers and the public from the transportation of waste is traffic accidents.

Health-and-safety effects other than fatalities were not explicitly accounted for in the analysis. Since potential illnesses and injuries were felt to be strongly correlated with fatal health effects, the implications of their inclusion were examined in sensitivity analyses that greatly increased the weight on fatalities in the evaluation. These analyses, described in Section 4.6, indicate that the inclusion of nonfatal health effects would not lead to any additional insights or change any implications of the analysis.

The performance measures were selected by panels of technical specialists (see Appendix A) with expertise in health physics; repository design, construction, and operation; air pollution; and transportation. For most of the

Table 4-1. Objectives and performance measures

Objective	Performance measure
HEALTH-AND-SAFETY IMPACTS	
1. Minimize worker health effects from radiation exposure at the repository	X_1: repository-worker radiological fatalities
2. Minimize public health effects from radiation exposure at the repository	X_2: public radiological fatalities from repository
3. Minimize worker health effects from nonradiological causes at the repository	X_3: repository-worker nonradiological fatalities
4. Minimize public health effects from nonradiological causes at the repository	X_4: public nonradiological fatalities from repository
5. Minimize worker health effects from radiation exposure in waste transportation	X_5: transportation-worker radiological fatalities
6. Minimize public health effects from radiation exposure in waste transportation	X_6: public radiological fatalities from transportation
7. Minimize worker health effects from nonradiological causes in waste transportation	X_7: transportation-worker nonradiological fatalities
8. Minimize public health effects from nonradiological causes in waste transportation	X_8: public nonradiological fatalities from transportation
ENVIRONMENTAL IMPACTS	
9. Minimize adverse aesthetic impacts	X_9: constructed scale (see Table 4-2)
10. Minimize adverse archaeological, historical, and cultural impacts	X_{10}: constructed scale (see Table 4-3)
11. Minimize adverse biological impacts	X_{11}: constructed scale (see Table 4-4)
SOCIOECONOMIC IMPACTS	
12. Minimize adverse socioeconomic impacts	X_{12}: constructed scale (see Table 4-5)
ECONOMIC IMPACTS	
13. Minimize repository costs	X_{13}: millions of dollars
14. Minimize waste-transportation costs	X_{14}: millions of dollars

health-and-safety performance measures, detailed analytical models are available and were used to evaluate the impact levels at each site. The inputs to the models, shown in the influence diagrams (see Appendix E), and the results calculated by the models were reviewed over several months by the appropriate specialists. In those instances where the data required for the models are limited or not comparable from site to site, professional judgment was used to supplement calculations. This is explained in more detail in Appendix F.

4.2.2 ENVIRONMENTAL PERFORMANCE MEASURES

It was necessary to construct performance measures to indicate the degree to which the three environmental objectives are achieved. These constructed scales are presented in Tables 4-2, 4-3, and 4-4. The performance measure for aesthetic degradation is mainly concerned with the visual disturbances or the noise experienced by people living in or visiting the area of a site. The performance measure for impacts on archaeological, historical, and cultural properties is concerned with the number of such properties that would be affected and the significance of the impact. The possibility of mitigating such impacts is included in this performance measure, and it is assumed that such mitigation, where possible, would definitely occur. The performance measure for adverse biological impacts is concerned with adverse impacts on threatened and endangered species, on biologically sensitive species, or on the habitats of either; it is also concerned with any resultant threats to the regional abundance of the species.

A panel of technical specialists (see Appendix A) worked with decision analysts over several months to construct the scales for the performance measures. A first step in this process was the development of influence diagrams to identify the fundamental characteristics of a site that determine its ability to meet objectives (see Appendix E). These fundamental characteristics were then used as the basis for the constructed scales. The descriptions of the specific impact levels for the constructed scales were revised many times to ensure that the assignment of the impact levels could be traced and appraised by other professionals given the appropriate information.

As can be seen from Tables 4-2, 4-3, and 4-4, there are seven levels of impact for the performance measure describing adverse aesthetic impacts and six levels for the other environmental performance measures. The levels of impact are defined so that level 0 corresponds to no impact and higher levels designate increasingly adverse impacts.

4.2.3 SOCIOECONOMICS PERFORMANCE MEASURE

The socioeconomics performance measure is also a constructed scale concerned with the impact of the repository on the local communities, the infrastructure of those communities, the ability of people in those communities to retain the lifestyle they are accustomed to, and the indirect economic implications to persons in the local communities. It consists of a constructed scale of five levels (see Table 4-5). Level 0 corresponds to essentially no adverse socioeconomic impact, and higher levels designate a greater level of adverse impact.

The constructed scale was developed by a panel of technical specialists with expertise in socioeconomics and institutional analysis (see Appendix A) and decision analysts in a process that took several months. To guide the specification of the performance measure, an influence diagram (Figure E-12 in Appendix E) was constructed. An effort was made to make the descriptions of impact levels specific enough to represent and communicate distinct socioeconomic impacts of significance.

Table 4-2. Performance measure for adverse aesthetic impacts from the the repository and waste transportation

Impact level	Aesthetic impacts in the affected area[a,b]
0	None
1	One minor effect
2	Two minor effects
3	Three minor effects
4	One major effect
5	Two major effects
6	Three major effects

[a]Major effects are defined as the following:

- The affected area contains components of the National Park system, National Wildlife Refuge system, National Wild and Scenic River system, National Wilderness Preservation system, National Forest Lands, or a comparably significant State resource area, or an aesthetic resource that is unique to the area. The locations of such components are such that--
  - Four or more key observation points or sensitive-receptor areas within the resource area are on the line of sight or within audible distance of the project and/or
  - Some key observation points or sensitive-receptor areas on the line of sight or within audible distance of the project attract many visitors.
- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that these points are on the project's line of sight and are within a visual setting that would significantly contrast with the project.
- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that the project would be audible and would exceed established noise criteria.

[b]Minor effects are defined as the following:

- The affected area contains components of the National Park system, National Wildlife Refuge system, National Wild and Scenic River system, National Wilderness Preservation system, National Forest Lands, or a comparably significant State resource area, or an aesthetic resource that is unique to the area. The locations of such components are such that—
  - Three or fewer key observation points or sensitive-receptor areas within the resource area are on the line of sight or within audible distance of the project and/or
  - No key observation points or sensitive-receptor areas on the line of sight or within audible distance of the project attract many visitors.
- The locations of residences, population centers, major vistas, national or cultural landmarks, public recreation areas, or public highways are such that these points are on the project's line of sight but are within a visual setting that would not significantly contrast with the project.
- The locations of residences, population centers, major vistas, natural or cultural landmarks, public recreation areas, or public highways are such that the project would be audible but would not exceed established noise criteria.

Table 4-3. Performance measure for adverse archaeological, historical, and cultural impacts from the repository and waste transportation

Impact level	Impacts on historical properties in the affected area[a]
0	There are no impacts on any significant historical properties
1	One historical property of major significance or five historical properties of minor significance are subjected to adverse impacts that are minimal or amenable to mitigation
2	Two historical properties of major significance or ten historical properties of minor significance are subjected to adverse impacts that are minimal or amenable to mitigation
3	Two historical properties of major significance or ten historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated
4	Three historical properties of major significance or 15 historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated
5	Four historical properties of major significance or 20 historical properties of minor significance are subjected to adverse impacts that are major and cannot be adequately mitigated

[a] The performance measure is defined by the following:

- Historical property of minor significance: A historical property that is of local or restricted significance, but does not meet the criteria of significance for the National Register of Historic Places (e.g., a homestead or miner's cabin that is of local importance but does not meet the criteria of the National Register; an archaeological site that is representative of a period of time for which there are many examples).

- Historical property of major significance: A historical property that meets the criteria of significance for the National Register of Historic Places (e.g., first town hall in a community; cave sites representative of an Indian people at one stage of their history; a Civil War battlefield) or a religious site highly valued by an Indian group (e.g., an Indian burial ground).

- Minimal impacts: Impacts that may alter the historical property, but will not change its integrity or its significance.

- Major impacts: Impacts that change the integrity or the significance of the historical property.

- Amenable to mitigation: The character of the historical property is such that it is possible to mitigate adverse impacts, reducing major impacts to minor or eliminating adverse impacts (e.g., impacts on an archaeological site that is significant because of the data it contains can be mitigated by excavating and analyzing those data; subsurface sites located within the controlled area may be protected under agreements made to guarantee that they will not be disturbed; a historical site can be adequately protected from vandals by erecting physical barriers).

- Not amenable to mitigation: The character of the historical property is such that impacts cannot be adequately mitigated because the value depends on the relationship of the historical property to its environment (e.g., a historical property of religious significance; a historical property that has value beyond the data contained; an archaeological site that is too complex for adequate excavation given state-of-the-art techniques).

Table 4-4. Performance measure for adverse biological impacts from the repository and waste transportation

Impact level	Biological impacts in the affected area
0	No damage to species of plants or wildlife that are desirable, unique, biologically sensitive, or endangered or to any biological resource areas that provide habitats for such species.
1	Damage to, or destruction of, individuals of desirable species or portions of biological resource areas that provide habitats for the species, but such species or resource areas are nonunique, nonsensitive, nonendangered, and common throughout the region.
2	Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas does not threaten their regional abundance. Other affected biological resources are not unique in the region.
3	Threatened and endangered (T&E) species and/or habitats for T&E species are in the affected area. The damage to, or the destruction of, individuals of the T&E species or portions of the habitat does not threaten their regional abundance or Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are not unique in the region.
4	Threatened or endangered species and/or habitats for T&E species are in the affected area. The damage to, or the destruction of, individuals of the T&E species or portions of the habitats does not threaten their regional abundance and Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are not unique in the region.
5	Threatened and endangered (T&E) species and/or habitats for T&E species are in the affected area. The damage to, or the destruction of, individuals of the T&E species or portions of the habitats threatens their regional abundance and Biologically sensitive species or resource areas are in the affected area. The damage to, or the destruction of, individuals of these sensitive species or portions of such resource areas threatens their regional abundance. Other affected biological resources are unique in the region.

Table 4-5. Performance measure for adverse socioeconomic impacts from the repository and waste transportation

Impact level	Socioeconomic impacts in the affected area[a]
0	In-migrating population of 2000 persons is dispersed over a broad region with a population of 100,000. The public infrastructure[b] is adequate for repository-related growth. The transportation infrastructure[c] and the housing supply are also adequate. Because of the large population base and diverse lifestyles, values, and social structures, social disruptions are not expected. Direct and indirect employment of 1500 persons during repository operation, in a region with a total employment of 60,000, is not expected to lead to the economy of the area becoming overly dependent on the repository. Repository activities are not incompatible with existing land uses,[d] and no adverse impacts on water resources are expected. All land is State or federally owned, and no commercial, residential, or agricultural displacement is expected.
1	In-migrating population of 5000 persons is dispersed over an area with a population of 50,000. Moderate upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in the affected area. Moderate (2 percent) increase in housing supply is required to accommodate growth. Despite the expected population growth, in-migrants have lifestyles and values that are expected to match those of current residents; major social disruptions are not expected. Direct and indirect employment of 3000 persons during repository operation in a region with a total employment of 30,000 and a moderately diverse economy is not expectd to lead to a disruption of existing business patterns and economic dependence that cannot be avoided by applying standard economic-planning measures. Repository activities are not incompatible with existing land uses,[d] and no adverse impacts on water resources are expected. One-quarter of the land is privately owned, and minimal commercial, residential, or agricultural displacement is expected.
2	In-migrating population of 5000 persons is concentrated in a few communities in an area with a population of 50,000. Major upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in affected communities. A 10-percent increase in housing is also expected. More than a quarter of the residents have lifestyles and values that are unlikely to match those of in-migrants. Direct and indirect employment of 3000 during repository operation in a region with a total employment of 30,000 and a moderately diverse economy is not expected to lead to a disruption of existing business patterns and economic dependence that cannot be avoided by applying standard economic-planning measures.

Table 4-5. Performance measure for adverse socioeconomic impacts from the repository and waste transportation (continued)

Impact level	Socioeconomic impacts in the affected area[a]
2 (continued)	Repository activities are somewhat incompatible with existing land uses,[d] and minor impacts are expected; minor diversion of water resources from other activities is also expected.
	Half of the land is privately owned, and commercial, residential, or agricultural displacement is expected.
3	In-migrating population of 10,000 persons is concentrated in a few communities within an area with a population of 10,000. Major upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in affected communities. Considerable new housing (a 75-percent increase) is also expected.
	Affected communities have homogeneous lifestyles, values, and social structures that do not match those of the in-migrants; conflict between current and new residents is expected.
	Direct and indirect employment during repository operation of 5000 persons in a region with 5000 employees is expected to disrupt existing business patterns and to lead to substantial economic decline after the completion of waste-emplacement operations.
	Negative impacts are expected on existing land uses,[d] and minor diversion of water resources from other activities is expected.
	All land is privately owned, and commercial, residential, or agricultural displacement is expected.
4	In-migrating population of 10,000 persons is concentrated in a few communities in an area with a population of 10,000. Major upgrading of the public infrastructure[b] and of the transportation infrastructure[c] is required to accommodate repository-related growth in the affected communities. Considerable new housing (a 75-percent increase) is also expected.
	Affected communities have homogeneous lifestyles, values, and social structures that do not match those of the in-migrants; conflict between current and new residents is expected.
	Direct and indirect employment during repository operation of 5000 in a region with 5000 employees is expected to disrupt existing business patterns and to lead to substantial economic decline after the completion of waste-emplacement operations.
	Repository activities are incompatible with existing land uses,[d] and negative impacts are expected; major diversion of area water resources is likely, resulting in impacts on development in the affected area.
	All land is privately owned, and commercial, residential, or agricultural displacement is expected.

[a] Socioeconomic impacts equivalent to those listed in the table.

[b] The public infrastructure includes schools; medical facilities; police and fire services; water, sewer, and solid-waste systems; and recreation facilities.

[c] The transportation infrastructure includes roads, public transportation facilities, and the like.

[d] Examples of existing land uses are agricultural and residential uses, uses related to tourism, and uses related to local recreation.

4.2.4 COST PERFORMANCE MEASURES

The repository costs include the cost of siting, construction, operation, closure, and decommissioning. These activities will take place over a period of approximately 80 years. Transportation operations will span about 30 years, starting in 1998. The cost performance measures are millions of nondiscounted dollars for the repository and for waste transportation. Nondiscounted costs rather than discounted costs were chosen as performance measures because, for various reasons, the latter would not produce more insights from the analysis (see Section F.4.1). The reasons include large uncertainties about inflation rates and component escalation costs, the time when expenditures are made, and the appropriate discount rate.

Analytical models were used to estimate the costs of repository construction and operation and of transportation operations for each of the sites. Technical specialists with expertise in these areas reviewed both the data used in the models and the results--again over a period of several months. The specialists are identified in Appendix A, and the models are described in Appendix F.

4.3 DESCRIPTIONS OF POSSIBLE SITE IMPACTS

The possible impacts for each of the five sites for each of the 14 performance measures are presented in Table 4-6; both a base-case estimate and a range consisting of a high estimate and a low estimate are given. The base case is meant to describe the expected performance of a given site with respect to a given performance measure. Because there is uncertainty about the possible impacts, the range is included to indicate the significance of that uncertainty. The ranges were determined with the intent that they would have a 90-percent chance of encompassing the actual impacts exerted by a repository at the site. Consider, for instance, the repository-cost performance measure for the Yucca Mountain site in Table 4-6. The base-case estimate is 7500 million dollars (i.e., 7.5 billion dollars), and the range is from 4875 to 10,125 million dollars. This means that, if a repository is eventually developed at Yucca Mountain, the current judgment is that the estimated cost of construction and operation will have a 90-percent chance of falling between 4875 and 10,125 million dollars. Very brief comments on the base-case impacts and their uncertainties are presented below. The impacts are based on information in the environmental assessments of the five nominated sites (DOE, 1986a-e). Details on the logic underlying the estimates are provided in Appendix F.

The five panels of technical specialists who developed the preclosure performance measures also estimated the impacts for all five sites. The process of estimating the site impacts against each performance measure began in mid-December 1985 and continued through March 1986. A first step was the gathering of a consistent set of site data from the environmental assessments, using the previously developed influence diagrams and performance measures as guides. "Consistent set" means a common set of assumptions, level of detail, level of conservatism, etc. Workshops were then held to generate initial estimates of site impacts and the ranges. Details of the process used to generate the final estimates of site impacts reported in Table 4-6 varied somewhat from panel to panel. Individual panel members in some instances wrote justifications for the

Table 4-6. Base-case estimates and ranges of site impacts[A]

Performance measure	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
X_1 = repository-worker radiological fatalities	2 (<1-4)	2 (<1-4)	2 (<1-4)	4 (<1-9)	9 (2-17)
X_2 = public radiological fatalities from repository	0.7 (0.3-1.5)	0.5 (0.1-1)	<0.1 (<0.1-0.2)	<0.1 (<0.1-<0.1)	0.7 (<0.1-1.5)
X_3 = repository-worker non-radiological fatalities	27 (17-36)	29 (19-39)	27 (17-36)	18 (12-24)	43 (28-58)
X_4 = public nonradiological fatalities from repository	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)	0 (0-0)
X_5 = transportation-worker radiological fatalities	0.52 (0-0.73)	0.64 (0-0.90)	0.73 (0-1.0)	0.81 (0-1.1)	0.9 (0-1.3)
X_6 = public radiological fatalities from transportation	2.4 (0-3.4)	2.9 (0-4.1)	3.5 (0-4.9)	4.1 (0-5.7)	4.3 (0-6.1)
X_7 = transportation-worker nonradiological fatalities	1.3 (0.6-2.1)	1.6 (0.73-2.6)	2.1 (0.96-3.4)	2.5 (1.1-4.0)	2.7 (1.2-4.3)
X_8 = public nonradiological fatalities from transportation	5.3 (2.4-8.5)	6.7 (3.1-10.8)	8.4 (3.9-13.5)	10.2 (4.7-16.4)	11.0 (5-17.7)
X_9 = aesthetic impacts (see Table 4-2)	4 (1-5)	4 (3-5)	6 (6-6)	4 (1-5)	1 (1-2)
X_{10} = archaeological, historical and cultural impacts (see Table 4-3)	0.5 (0-1)	1 (0-2.5)	3 (2.5-5)	2 (2-3.5)	0.5 (0.5-3)
X_{11} = biological impacts (see Table 4-4)	2.67 (2-3.5)	2.33 (1.5-3)	3.5 (2.67-4.5)	2 (1-2.67)	2.33 (1-3.5)
X_{12} = socioeconomic impacts (see Table 4-5)	2 (1-3)	1.67 (1-3)	2 (1.33-3)	0.67 (0.33-2)	0.33 (0-0.67)
X_{13} = repository cost (millions of dollars)	9000 (5850-12,150)	9500 (6175-12,825)	10,400 (6760-14,040)	7500 (4875-10,125)	12,900 (8385-17,415)
X_{14} = transportation cost (millions of dollars)	970 (260-2040)	1120 (300-2350)	1240 (330-2600)	1400 (380-2940)	1450 (390-3040)

[A]Ranges are given in parentheses.

initial estimates of impacts and then shared drafts with the other members of the panel. In some cases additional workshops were held to discuss the bases for the estimates or, more simply, comments were provided to the lead panel member.

The initial estimates were in many cases revised and the bases refined over the course of several months. In most cases a group consensus was achieved on the estimates of the base-case impacts and the ranges. If consensus was not achieved, differences in opinion over the appropriate estimates were used to set the range of impacts. In other instances--for example, for those performance measures where detailed, well-established analytical models could be used to calculate impacts--the full panel was able to reach consensus on the appropriate levels of impacts at one workshop. The remainder of the time was spent checking the data for the models, the assumptions, etc., and in writing and refining the reasoning for the estimates of site impacts.

4.3.1 HEALTH-AND-SAFETY IMPACTS

4.3.1.1 Repository

Workers at the repository receive radiation doses directly from the natural radioactivity of the rock and also from repository operations. From the number of workers involved in each of these situations, the expected radiation emitted, and assumptions about ventilation, the number of cancer fatalities attributable to the exposure of workers to radiation in the repository was calculated. The assumed dose-effect relationship is that 280 cancer fatalities are caused by every million man-rem of population dose (i.e., the sum of the individual doses received by all the members of a population). As discussed in Appendix F, a different dose-effect relationship would not affect the relative ranking of sites.

Radiological health effects in the public are due mainly to radionuclide releases from the repository and subsequent exposure through inhalation or ingestion. The population density within 50 miles of the sites is a key factor in determining the number of radiological fatalities.

Nonradiological worker fatalities at the repository are due to accidents during construction, operation, closure, or decommissioning. In this regard, it is known that mining is a hazardous occupation, even when a great deal of attention is paid to the safety of the workers.

A mechanism by which nonradiological fatalities in the public may result from repository construction and operation is air pollution. However, as seen from Table 4-6 and Appendix F, calculations show that air pollution would not cause any fatalities.

4.3.1.2 Transportation

Transportation assessments are based on the assumption that 70 percent of waste is transported by rail and 30 percent by truck. Although many logistics, economic, and service factors will be involved in the choice between rail and truck transportation more than 10 years hence, the DOE believes this is a reasonable assumption for the purpose of comparing sites. For either mode of transportation, there is a potential for accidents, and small amounts of radiation will be emitted. Both workers and the public will be exposed to any accidents and the released radiation. Estimates of the emitted radiation, the surrounding population densities, the dose-response relationship used for radiological effects from the repository, and the rates of train and truck accidents were used to calculate the base-case estimates of fatalities for the four performance measures characterizing the effects of transportation on health and safety.

The ranges of uncertainty for these four performance measures are due to uncertainty about the analytical models (see Appendix A of the environmental assessments for the nominated sites (DOE, 1986a-e) and Appendix F of this report), the assumptions used in calculating the impacts, and uncertainty about the location of a second repository. In a coordinated waste-management system, a second repository would presumably reduce the cost and risk of waste transportation because the waste could be sent to the nearest repository. The influence of a facility for monitored retrievable storage (MRS) on transportation assessments is not explicitly considered because the MRS facility is not authorized by the Congress at this time.

4.3.2 ENVIRONMENTAL IMPACTS

As mentioned, the environmental impacts were assessed by technical specialists familiar with the environmental assessments for each of the sites. These same people participated in constructing the performance measures.

Concerning the aesthetic impacts, it is necessary to consider potential observation points and sensitive-receptor areas, the location of people visiting or living near a repository, and any natural environmental features of significance. Then judgments must be made about where aesthetic impacts might occur and their significance. A detailed discussion of these judgments is given in Appendix F.

With regard to archaeological, historical, and cultural impacts, the first step is to characterize the number of historical properties of major and minor significance known to be in the vicinity of the nominated sites. Then the likely impact on each is considered as well as the possibilities of mitigating the impact. As a result of this assessment, the base-case impact given current information is specified. The range takes into account the possibilities of discovering additional historical properties at the various sites and of identifying better ways to mitigate potential damage to identified properties.

The appraisal of biological impacts is based on a description in the environmental assessments of the biological resources at the sites and the status of those resources (threatened and endangered, biologically sensitive, or species that are nonunique, nonsensitive, nonendangered, and common throughout the region).

4.3.3 SOCIOECONOMIC IMPACTS

Assessments of socioeconomic impacts are based on a knowledge of the population living in the vicinity of the nominated sites, the characteristics and lifestyles of various segments of that population, and the effects that an influx of money and people may have on those communities. In addition, there may be a disruption of local agriculture, local tourism, or employment opportunities. These are estimated from information in the environmental assessments and from a professional knowledge of what often occurs with a boom-bust cycle in rural communities.

4.3.4 ECONOMIC IMPACTS

Cost estimates for a repository at the various sites were developed by considering separately the costs of siting, construction, operation, and closure and decommissioning. The base-case cost estimates for the Yucca Mountain, Deaf Smith, and Hanford sites are taken from the most recent information (Weston, 1986) developed as part of the DOE's annual evaluation of the adequacy of the fee (1 mill per kilowatt-hour) collected from electric utilities for the Nuclear Waste Fund. For the Davis Canyon and the Richton Dome sites, site-specific cost estimates were prepared for this report. Details of these estimates are given in Appendix F. The ranges for repository costs are plus or minus 35 percent of the base-case estimates. This uncertainty reflects the currently available level of repository-design information (preconceptual stage). Although the DOE is reasonably confident about the ranking of the base-case cost estimates, it recognizes that a first-of-its-kind engineering project like a repository has a high potential for major design changes. These may lead to increases above current estimates.

The base-case estimates of transportation costs were generated with the assistance of a computer model (see Appendix F for details). The range on transportation costs was based on the assumption that a second repository may cause a 40-percent increase or a 46-percent decrease in costs. In addition, it was assumed that a 50-percent increase or decrease in costs should be attributed to uncertainty in the model and the assumptions used to calculate transportation costs.

4.4 THE MULTIATTRIBUTE UTILITY FUNCTION

The selection of sites for characterization would be easy if some sites were more desirable than others on every objective. However, this rarely happens with complex problems, and it did not happen with the five nominated sites. Hence, a key question is, "How much should be given up with regard to one objective to achieve a specified improvement in another?" This key issue is one of value tradeoffs. In addition, because of the uncertainties inherent in the problem, any given site is not guaranteed to yield a specific consequence. At each site there are circumstances that could lead to relatively desirable or undesirable consequences, and the question here is, "Are the potential benefits of having things go right worth the risks of having things go wrong?" This issue concerns attitudes toward risk. Both value tradeoffs and risk attitudes are particularly complicated because there are no right or wrong values. However, the multiattribute utility function can be used to aggregate implications in terms of the individual objectives, using value tradeoffs and attitudes toward risk.

This section presents the multiattribute utility function assessed for evaluating the nominated sites. Details of the assessment procedure are found in Appendix G. The perspective taken was that the sites should be evaluated in terms of minimizing adverse preclosure impacts through specific objectives concerning impacts on health and safety, the environment, socioeconomics, and costs.

The value judgments required to construct the multiattribute utility function were provided by four senior managers (identified in Appendix A) in the DOE's Office of Civilian Radioactive Waste Management, which is responsible for recommending sites for characterization to the Secretary of Energy. The assessment of the multiattribute utility function was done in structured discussions between decision analysts and the DOE managers. This process quantified value judgments about the possible consequences in the problem. The procedure systematically elicited information about value tradeoffs and risk attitudes, and it included many consistency checks. To develop the form of the multiattribute utility function, which is essentially a model of values, one uses value-independence concepts in the same way that probabilistic independence is used in structuring models of impacts. Part of the assessment procedure verified which independence assumptions were appropriate for the objectives used to evaluate the sites.

Given the assumptions verified in Appendix G, an appropriate multiattribute utility function is the additive form*

$$u(x_1,\ldots,x_{14}) = 121 - 1/200 \sum_{i=1}^{14} K_i C_i(x_i), \qquad (4\text{-}1)$$

where the C_i ($i = 1,\ldots,14$) are component disutility functions representing units of the respective performance measures with natural scales and percentage of the range of impacts for the constructed scales, and the K_i ($i = 1,\ldots,14$) are positive scaling factors representing the value tradeoffs between units of the corresponding performance measure and repository costs

*The more common way of writing the additive utility function u is

$$u(x_1,\ldots,x_{14}) = A + B \sum_{i=1}^{14} k_i u_i(x_i), \qquad (4\text{-}2)$$

where the u_i ($i = 1,\ldots,14$) are the component utility functions scaled from 0 to 1, the k_i ($i = 1,\ldots,14$) are scaling factors that sum to 1, and A and $B > 0$ are scaling constants chosen to scale u in a manner that facili- tates interpreting the results of the analysis.

As discussed in Appendix G, the k_i factors are difficult to interpret. For this problem, both because preferences decrease with increasing impact levels for all of the performance measures and because the component utility functions are linear for each of the performance measures with natural scales, a more intuitive expression of the utility function for this problem is Equation 4-1. In this expression, the scaling factors K_i ($i = 1,\ldots,14$) are directly interpretable as the assessed value tradeoffs and the C_i ($i = 1,\ldots,14$) are simply the units of impact. With Equation 4-2, the k_i and the u_i are derived from the value tradeoffs and the scaling convention for the problem. Since preferences decrease with increasing impact levels, the minus sign in front of the 1/200 term in Equation 4-1 is needed and the C_i can be interpreted as disutility functions.

measured in millions of dollars. The specific C_i and K_i values that were assessed are given in Table 4-7.

The factors 121 and -1/200 in Equation 4-1 are necessary to scale the utility from 0 to 100, where 100 is chosen to represent a particularly desirable set of impacts for all performance measures and 0 represents a particularly undesirable set of impacts for all performance measures. For this purpose, the ranges of the performance measures listed in Table 4-7 were chosen to be broad enough to include all possible impacts for the sites being evaluated. The utilities of 0 and 100 are assigned by Equation 4-1 to the sets of impacts represented by the highest levels and the lowest levels in Table 4-7, respectively. Because the utility function is additive and because the component utility function for repository cost is linear, it is particularly easy to interpret units, referred to as "utiles," of the multiattribute utility function (Equation 4-1) in terms of equivalent costs. Specifically, one utile is equivalent in value to 200 million dollars.

To get an intuitive feeling for the C_i and the K_i terms in Equation 4-1, some examples are helpful. The component disutility function C_1 for worker cancer fatalities from the repository is simply x_1, which represents the number of such fatalities. For aesthetic impacts, the component disutility function C_9 represents the percentage of the highest level of aesthetic impact described in Table 4-2. The highest level is level 6, so $C_9(6) = 100$. Since $C_9(4) = 33$, as shown in Table 4-7, aesthetic impacts of level 4 are assessed as being one-third as detrimental as impacts of level 6 (i.e., 33 is one-third of 100).

The value tradeoff K_8 is 4, which means that the impact of one statistical public fatality due to a transportation accident is deemed as undesirable as an additional cost of 4 million dollars. The value tradeoff $K_9 = 1$ means that the impact of an additional 1 percent of aesthetic degradation is deemed as undesirable as an additional cost of 1 million dollars. The value tradeoff $K_{14} = 1$ means that a million dollars in transportation cost is deemed equivalent to a million dollars in repository cost. That $K_{13} = 1$ is by definition.

The multiattribute utility function assessed in this problem can be interpreted as follows. In situations where there is uncertainty about the impacts, the expected (i.e., average) utility can be used to appraise the relative desirability of consequences (i.e., set of impact levels). Higher expected utilities indicate preferred alternatives. In addition, the assessment described in Appendix G indicates that the multiattribute utility function is also a measurable-value function. Hence, differences in utility have a useful interpretation. Namely, the relative differences in desirability between two consequences can be measured by the differences in utility between those consequences. Furthermore, the relative differences in desirability between two alternatives can be measured by the differences in expected utilities between those alternatives.

To calculate the utility of a consequence with the utility function (Equation 4-1), clearly the only variable term is

$$C(x_1,\ldots,x_{14}) = \sum_{i=1}^{14} K_i C_i(x_i), \qquad (4\text{-}3)$$

Table 4-7. Parameters in the base-case multiattribute utility function and equivalent-consequence function

Performance measure	Impact range		Utility-function components	
	Lowest level	Highest level	Value tradeoff K	Component disutility function C
X_1 = repository-worker radiological fatalities	0	30	1	x_1
X_2 = public radiological fatalities from repository	0	10	4	x_2
X_3 = repository-worker non-radiological fatalities	0	100	1	x_3
X_4 = public nonradiological fatalities from repository	0	10	4	x_4
X_5 = transportation-worker radiological fatalities	0	10	1	x_5
X_6 = public radiological fatalities from transportation	0	10	4	x_6
X_7 = transportation-worker non-radiological fatalities	0	10	1	x_7
X_8 = public nonradiological fatalities from transportation	0	20	4	x_8
X_9 = aesthetic impacts (see Table 4-2)	0	6	1	$C_9(0)=0$, $C_9(1)=3$, $C_9(2)=6$, $C_9(3)=9$, $C_9(4)=33$, $C_9(5)=67$, $C_9(6)=100$
X_{10} = archaeological, etc., impacts (see Table 4-3)	0	5	0.2	$C_{10}(0)=0$, $C_{10}(1)=12$, $C_{10}(2)=23$, $C_{10}(3)=56$, $C_{10}(4)=78$, $C_{10}(5)=100$
X_{11} = biological impacts (see Table 4-4)	0	5	0.3	$C_{11}(0)=0$, $C_{11}(1)=4$, $C_{11}(2)=10$, $C_{11}(3)=18$, $C_{11}(4)=40$, $C_{11}(5)=100$
X_{12} = socioeconomic impacts (see Table 4-5)	0	4	5	$C_{12}(0)=0$, $C_{12}(1)=8$, $C_{12}(2)=20$, $C_{12}(3)=60$, $C_{12}(4)=100$
X_{13} = repository cost (millions of dollars)	4000	19,000	1	x_{13}
X_{14} = transportation cost (millions of dollars)	200	4200	1	x_{14}

which can be thought of as an equivalent-consequence function. With this function, higher numbers represent more-severe consequences and are less preferred. Because the multiattribute utility function is additive and the utility function for cost is linear, each unit of the equivalent consequence calculated with Equation 4-3 can be taken to be as undesirable as an additional cost of 1 million dollars.

4.5 EVALUATION OF THE NOMINATED SITES

The impacts of the five sites in terms of the performance measures are combined with the value judgments expressed in the multiattribute utility function to provide an overall evaluation of the desirability of the sites. The first part of this section presents aggregations of informative performance-measure categories. The complete base-case analysis follows in the second part. Numerous sensitivity analyses involving changes in the possible impacts and also changes in the multiattribute utility function for evaluating these impacts are presented in Section 4.6.

4.5.1 BASE-CASE ANALYSIS

Table 4-8 uses the component disutility functions in Table 4-7 to convert the base-case estimates of impacts for each site to component disutilities. These can be easily substituted into the utility function (Equation 4-1) or the equivalent-consequence function (Equation 4-3) to evaluate the sites. The component disutilities are identical with the base-case estimates of impacts in Table 4-6 except for the environmental and socioeconomic performance measures. To calculate the equivalent consequence for a site, Equation 4-3 is used. For each site, the appropriate K_i value from Table 4-7 is multiplied by the appropriate C_i value from Table 4-8 to obtain the equivalent-consequence impacts for each performance measure in Table 4-9. Before examining these results for all five sites, let us look at the calculations for the Richton Dome site.

In Table 4-8, the number of nonradiological public fatalities from transportation to Richton Dome, represented by performance measure X_8, is 5.3. In Table 4-7, the value tradeoff K_8 between units of this performance measure and costs is 4, indicating that 4 million dollars in additional cost is indifferent to a statistical nonradiological public fatality from transportation. Hence, the 5.3 fatalities is multiplied by the 4 million dollars per fatality to yield a 21.2 contribution to the equivalent-consequence impact associated with performance measure X_8 for the Richton Dome site (Table 4-9). Regarding socioeconomic impacts (X_{12}), impact level 2 in Table 4-5 describes that impact at Richton Dome. This has a disutility of 20, as shown in Table 4-8. The value tradeoff K_{12} for a unit (i.e., percent) of socioeconomic impacts is 5 million dollars, as indicated in Table 4-7. Multiplying 20 by 5 yields the contribution of 100 to the equivalent-consequence impact for performance measure X_{12} in Table 4-9. The rest of the entries in Table 4-9 in the column for the Richton Dome site can be calculated similarly.

Table 4-8. Base-case component disutilities of nominated sites[a]

	Performance measure	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
X_1 =	repository-worker radiological fatalities	2	2	2	4	9
X_2 =	public radiological fatalities from repository	0.7	0.5	0.1	0.1	0.7
X_3 =	repository-worker non-radiological fatalities	27	29	27	18	43
X_4 =	public nonradiological fatalities from repository	0	0	0	0	0
X_5 =	transportation-worker radiological fatalities	0.52	0.64	0.73	0.81	0.90
X_6 =	public radiological fatalities from transportation	2.4	2.9	3.5	4.1	4.3
X_7 =	transportation-worker nonradiological fatalities	1.3	1.6	2.1	2.5	2.7
X_8 =	public nonradiological fatalities from transportation	5.3	6.7	8.4	10.2	11
X_9 =	aesthetic impacts	33	33	100	33	3
X_{10} =	archaeological, historical, and cultural impacts	6	12	56	23	6
X_{11} =	biological impacts	15	12	29	10	12
X_{12} =	socioeconomic impacts	20	16	20	6	3
X_{13} =	repository cost	9000	9500	10,400	7500	12,900
X_{14} =	transportation cost	970	1120	1240	1400	1450

[a]Component disutilities are calculated by substituting the base-case estimates of impacts shown in Table 4-6 into the component disutility function in Table 4-7.

Table 4-10 aggregates the information in Table 4-9 in numerous ways to gain insights into the comparative advantages and disadvantages of the sites in informative performance-measure categories. Row 1 of Table 4-10 shows that the relative ranking of the nominated sites on preclosure radiological safety is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The difference between the first-ranked site and the fifth-ranked site is equivalent to 15 million dollars, a difference largely attributable to waste transportation.

Row 2 of Table 4-10 shows that the relative ranking of sites on worker fatalities (radiological and nonradiological) is Yucca Mountain, Richton Dome, Davis Canyon, Deaf Smith, and Hanford. The Yucca Mountain site is slightly

Table 4-9. Base-case equivalent-consequence impacts[a]

Performance measure	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
X_1 = repository-worker radiological fatalities	2	2	2	4	9
X_2 = public radiological fatalities from repository	2.8	2	0.4	0.4	2.8
X_3 = repository-worker non-radiological fatalities	27	29	27	18	43
X_4 = public nonradiological fatalities from repository	0	0	0	0	0
X_5 = transportation-worker radiological fatalities	0.52	0.64	0.73	0.81	0.90
X_6 = public radiological fatalities from transportation	9.6	11.6	14	16.4	17.2
X_7 = transportation-worker nonradiological fatalities	1.3	1.6	2.1	2.5	2.7
X_8 = public nonradiological fatalities from transportation	21.2	26.8	33.6	40.8	44
X_9 = aesthetic impacts	33	33	100	33	3
X_{10} = archaeological, historical, and cultural impacts	1.2	2.4	11.2	4.6	1.2
X_{11} = biological impacts	4.5	3.6	8.7	3.0	3.6
X_{12} = socioeconomic impacts	100	80	100	30	15
X_{13} = repository cost	9000	9500	10,400	7500	12,900
X_{14} = transportation cost	970	1120	1240	1400	1450

[a] Equivalent-consequence impacts in million of dollars are computed by multiplying the base-case component disutilities shown in Table 4-8 by the value tradeoffs shown in Table 4-7.

preferred to the three salt sites, which are barely distinguishable from one another, while the Hanford site is notably less favorable. This marked difference is attributable to nonradiological fatalities in repository workers (mostly from mining accidents), which, in turn, reflects the larger labor requirements for repository construction and operation at the Hanford site.

Row 3 of Table 4-10 aggregates the health-and-safety impacts on the public. The relative ranking is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The differences between the sites range from the equivalent of 6 to 30 million dollars and are largely attributable to waste transportation.

Table 4-10. Base-case equivalent-consequence impacts for various aggregations of performance measures[a]

Row	Performance-measure category[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
1	Radiological fatalities (X_1, X_2, X_5, X_6)	15	16	17	22	30
2	Worker fatalities (X_1, X_3, X_5, X_7)	31	33	32	25	56
3	Public fatalities (X_2, X_4, X_6, X_8)	34	40	48	58	64
4	Health and safety (X_1 through X_8)	64	74	80	83	120
5	Environment and socioeconomics (X_9 through X_{12})	139	119	220	71	23
6	Public near site (X_2, X_4, X_9 through X_{12})	142	121	220	71	26
7	Site impacts (X_1 through X_4, X_9 through X_{12})	171	152	249	93	78
8	Noncosts (X_1 through X_{12})	203	193	300	154	142
9	Noncosts and transportation costs (X_1 through X_{12}, X_{14})	1,173	1,313	1,540	1554	1,592
10	Noncosts and repository costs (X_1 through X_{12}, X_{13})	9,203	9,693	10,700	7654	13,042
11	Total equivalent impact (X_1 through X_{14})	10,173	10,813	11,940	9054	14,492

[a]The numbers in this table represent the equivalent-consequence impacts in millions of dollars rounded to the nearest unit. The numbers for certain categories (e.g., row 4) do not add because of rounding off.

[b]See Table 4-1 for definitions of the performance measures X_1 through X_{14}.

Row 4 of Table 4-10 shows that the relative ranking of sites against all health-and-safety impacts is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. In terms of equivalent-consequence impacts, the difference between the sites ranked first and fourth (equivalent to 19 million dollars) is about half the difference between the sites ranked fourth and fifth (equivalent to 37 million dollars).

Row 5 of Table 4-10 shows that the relative ranking of sites on all of the environmental and socioeconomics performance measures is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. The difference between the sites ranked fourth and fifth, Richton Dome and Davis Canyon, respectively, is most significant, equivalent to 81 million dollars (about 70 percent of the difference between the sites ranked first and fourth).

Row 6 of Table 4-10 aggregates the impacts that might be considered as adverse impacts on the public living near a site. It shows that the relative ranking of sites is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and

Davis Canyon--the same ranking as that obtained by considering only environmental and socioeconomic impacts. The most significant difference is between the sites ranked fourth and fifth--that is, Richton Dome and Davis Canyon. Row 7 of Table 4-10 includes the health-and-safety impacts on the workers at the repository and hence might be considered an aggregation of the total impact felt by all members of the community near a site. The ranking remains Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon.

If all noncost performance measures are aggregated, as in row 8 of Table 4-10, the relative ranking is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. Again, the most significant difference is between the sites ranked fourth and fifth; this difference is equivalent in value to 97 million dollars. This difference is larger than that between the sites ranked first and fourth (equivalent to 61 million dollars). This ranking is changed drastically by the addition of costs. When transportation costs are combined with the noncost performance measures, the ranking becomes Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford (row 9, Table 4-10). When repository costs are combined with the noncost performance measures, the ranking becomes Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford (row 10, Table 4-10). When both transportation and repository costs are combined with the noncost performance measures (i.e., all performance measures are considered), the ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford (row 11, Table 4-10).

4.6 SENSITIVITY ANALYSES

Many sensitivity analyses can be conducted to determine which of the impacts and value judgments are critical to any implications drawn from the analysis. This section presents several sensitivity analyses to determine the main factors that may influence these implications. In most cases the sensitivity analyses examine the effects of changing impact levels and value judgments on the total equivalent-consequence impacts (row 11, Table 4-10). The first set of sensitivity analyses focuses on changes in the impacts from the base case described in Table 4-6. The second set of sensitivity analyses examines changes in the multiattribute utility function for evaluating impacts.

4.6.1 SENSITIVITY ANALYSES INVOLVING IMPACTS

Given the base-case impacts and the elicited value judgments about them, the implications of the analysis seem most likely to be affected by changes in socioeconomic impacts, transportation-related impacts, and repository cost. Each of these, as well as other situations, are considered below. These sensitivity analyses examine the significance of uncertainties about preclosure impacts to the relative desirability of sites. The insensitivity of the implications of the analysis to the level of impact within the specified ranges of Table 4-6 is the main justification for the degree to which preclosure uncertainties are examined in the analysis.

4.6.1.1 Socioeconomic impacts

In one sensitivity analysis, the socioeconomic impacts in Table 4-6 were changed from the base-case estimate to the high estimate and then to the low estimate. Thus, for example, for the high estimate, the socioeconomic impact of the Deaf Smith site was specified as level 3 rather than the base-case level 1.67, and the impact of the Yucca Mountain site was specified as level 2 rather than the base-case level 0.67. The equivalent-consequence impacts of the five sites for these cases are shown in Table 4-11. Yucca Mountain remains the most favorable site, the salt sites still maintain the same order as in the base case, and Hanford is still the least favorable site for both changes. Indeed, if the socioeconomic impacts for any site are set at the low level while for all other sites they are set at the high level, there is no change in the overall ranking of sites.

Table 4-11. Sensitivity of total equivalent-consequence impacts to socioeconomic impacts[a]

Socioeconomic impact level	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Low level	10,113	10,773	11,900	9039	14,477
Base case	10,173	10,813	11,940	9054	14,492
High level	10,373	11,033	12,140	9124	14,507

[a]The numbers in this table represent the total equivalent-consequence impacts in million of dollars, with socioeconomic impact levels as indicated and all other performance measures at the base-case level.

4.6.1.2 Low transportation impacts

Because of the uncertainty about the second geologic repository, it seemed prudent to examine the implications of a low-transportation-impact scenario. The performance measures related to transportation are X_5 through X_8 and X_{14}. When all impacts for these performance measures are set at the low level of their ranges in Table 4-6, the equivalent-consequence evaluations shown in row 1 of Table 4-12 result. Again, the salt sites maintain the ranking Richton Dome, Deaf Smith, and Davis Canyon. Yucca Mountain is preferred to Richton Dome by the equivalent of 1448 million dollars, and Deaf Smith is preferred to Hanford by 3424 million dollars.

If in addition to the low transportation impacts the socioeconomic impacts are moved to the high (i.e., least desirable) level, the equivalent-consequence impacts in row 2 of Table 4-12 result. Again, Yucca Mountain is the preferred site, and the ranking of the salt sites is maintained. The Hanford site is still a distant fifth. If for the low-transportation-impacts

Table 4-12. Sensitivity of the total equivalent-consequence impacts to transportation impacts and varied socioeconomic impacts[a]

Row	Impact level[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
1	X_5 through X_8 and X_{14} low level, X_{12} base-case level	9,441	9,965	10,996	7993	13,389
2	X_5 through X_8 and X_{14} low level, X_{12} high level	9,641	10,185	11,196	8063	13,404
3	X_5 through X_8 and X_{14} low level, X_{12} low level	9,381	9,925	10,956	7978	13,374
4	Base case	10,173	10,813	11,940	9054	14,492

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars of all performance measures at their base-case levels except those indicated in the "impact level" column.

[b]Table 4-1 for definitions of the performance measures X_5, X_8, etc.

scenario the socioeconomic impacts are placed at their low level, the equivalent-consequence impacts that result are shown in row 3 of Table 4-12. These results are identical with those obtained when the socioeconomic impacts are placed at their base-case levels for the low-transportation-impact scenario.

4.6.1.3 Repository costs

Because the repository costs have such a wide range in uncertainty (i.e., in the billions of dollars), they have a significant effect on the equivalent-consequence impacts. This does not necessarily imply, however, that this uncertainty has a significant effect on the relative ranking of the sites or the implications of the analysis for selecting three sites for characterization. Table 4-13 illustrates this.

Table 4-13. Sensitivity of the total equivalent-consequence impacts to repository costs[a]

Repository-cost impact level	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Low level	7,023	7,488	8,300	6,429	9,977
Base-case level	10,173	10,813	11,940	9,054	14,492
High level	13,323	14,138	15,580	11,679	19,007

[a]The numbers in the table represent the total equivalent-consequence impacts in millions of dollars of all performance measures at their base-case level except for repository cost, which is at the level indicated.

If the repository cost for each site is set at the low level, the equivalent consequence of each site decreases from the base case. The ranking of the sites does not change, though the specific differences in equivalent-consequences among the sites are narrowed. The differences are, however, still very significant. If the repository cost for each of the sites is set at its high level, the equivalent-consequence implications are again identical with those for the base case.

Even when their repository costs are at the high levels, Yucca Mountain, Richton Dome, and Deaf Smith are still more favorable than Hanford with the repository cost at the base-case level. On the other hand, if the cost of the Hanford site is at its low level and the costs for the other sites are at the base-case levels, Hanford is slightly preferred to Richton Dome but less preferred than Yucca Mountain. In general, however, one expects a positive correlation between the costs of constructing a repository at any of the sites. Thus this scenario appears very unlikely.

4.6.1.4 Ranges of other noncost performance measures

If all of their noncost performance measures are moved to the high levels of their ranges in Table 4-6, the Richton Dome and the Deaf Smith sites would still be preferred to the Davis Canyon site even if its noncost impacts are assumed to be low. If all of the noncost performance measures are at their high levels for Richton Dome and all of these performance measures are at their low levels for Deaf Smith, Richton Dome is still preferable to Deaf Smith. Similarly, even if all of the noncost impacts of Yucca Mountain are set at their high levels and all of the noncost impacts of the Hanford site are set at their low levels, the Yucca Mountain site would still be more favorable than the Hanford site. The results of several sensitivity analyses are shown in Table 4-14.

Table 4-14. Sensitivity analysis of performance measures other than repository cost[a]

Impact level[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
High except X_{13} and X_{14} at base case	10,445	11,111	12,200	9,211	14,588
Low except X_{13} and X_{14} at base case	10,045	10,704	11,847	8,957	14,407
High except X_{13} at base case	11,515	12,341	13,560	10,751	16,178
Low except X_{13} at base case	9,335	9,884	10,937	7,937	13,347

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars of performance measures set at the levels indicated.
[b]X_{13} and X_{14} are repository cost and waste-transportation cost, respectively.

4.6.2 SENSITIVITY ANALYSES INVOLVING VALUE JUDGMENTS

The sensitivity analyses described below investigated the implications of different value tradeoffs between key performance measures, possible risk-averse and risk-prone attitudes, and the form of the overall multiattribute utility function.

4.6.2.1 Value tradeoffs among statistical fatalities

As shown in Table 4-7, the base-case value tradeoff for worker fatalities was that an additional cost of 1 million dollars is equivalent to one statistical worker fatality; for public fatalities the value tradeoff is an additional cost of 4 million dollars for one statistical public fatality. Furthermore, the base case assumed that these tradeoffs were identical for both radiological and nonradiological fatalities. Four variations of these base-case value tradeoffs were considered in the sensitivity analyses. The first two sensitivity analyses varied the value tradeoff for a public fatality versus a worker fatality from a ratio of 1:1 to 20:1, implying that the statistical fatality of a member of the public was equivalent to an additional cost of 1 million dollars in the first case and 20 million dollars in the second case. The next two sensitivity analyses varied the relative value on radiological and nonradiological fatalities from a ratio of 3:1 to 1:3.

Table 4-15 shows the results in terms of the equivalent-consequence evaluations for the four cases, as well as the base case repeated from Table 4-10. The results show almost the same relative ranking in all situations (although the spread between sites changes) except for the case where a worker fatality and a public fatality are valued equally. In this case the Yucca Mountain site is slightly more favorable than the Davis Canyon and the Deaf Smith sites, whereas the reverse holds in the base case. These differences, however, have no effect at all on the overall rankings of the sites.

4.6.2.2 Value tradeoffs between statistical fatalities and costs

Because of the importance to everyone of the value tradeoffs between statistical fatalities and costs, it is prudent to examine the implications of a wide range of these value tradeoffs. The base-case value tradeoffs were increased by factors of 5 and 25 in two sensitivity analyses. In the former case, the value tradeoffs for statistical public and worker fatalities were set at 20 and 5 million dollars, respectively. In the latter case, these value tradeoffs were 100 and 25 million dollars, respectively. The equivalent-consequence implications for health-and-safety impacts are presented, along with the base case, in Table 4-16. The implications of these changes are identical with those of the base case. In all cases, the overall site rankings are Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford.

Table 4-15. Sensitivity analysis of value tradeoffs among statistical fatalities

Variation from base case	Value tradeoff (millions of dollars per fatality)				Site[A]				
	Worker radiological (K_1,K_5)	Worker nonradiological (K_2,K_6)	Public radiological (K_3,K_7)	Public nonradiological (K_4,K_8)	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
None (i.e., base case)	1	1	4	4	64	74	80	83	120
1 public fatality = 1 worker fatality	1	1	1	1	39	43	44	40	72
1 public fatality = 20 worker fatalities	1	1	20	20	199	235	272	313	376
1 radiological fatality = 3 nonradiological fatalities	3	1	12	4	94	106	114	126	179
1 nonradiological fatality = 3 radiological fatalities	1	3	4	12	163	188	205	206	299

[A] The numbers in these columns represent equivalent-consequence impacts in millions of dollars for the base-case health-and-safety impacts, given the value tradeoffs stated in the table.

Table 4-16. Sensitivity analysis of value tradeoffs between statistical fatalities and costs

Variation from base case	Value tradeoff (millions of dollars per fatality) Worker (K_1,K_3,K_5,K_7)	Public (K_2,K_4,K_6,K_8)	Site[A] Richton Dome	Deaf Smith	Davis Canyon	Yucca Mountain	Hanford
Base case	1	4	64	74	80	83	120
5 times base case	5	20	320	370	400	415	600
25 times base case	25	100	1600	1850	2000	2075	3000

[A] The numbers in these columns represent equivalent-consequence impacts in millions of dollars for the base-case health-and-safety impacts, given the value tradeoffs stated in the table.

4.6.2.3 Value tradeoffs between socioeconomic impacts and costs

The base-case value tradeoff between costs and socioeconomic impacts is that to reduce the maximum level of socioeconomic impacts to zero is equivalent to 500 million dollars. If this value tradeoff is doubled to 1000 million dollars, the equivalent-consequence evaluations in Table 4-17 result. There is no change in the relative ranking of the sites.

The multiattribute utility function can be changed simultaneously with changes in possible impacts. The low-transportation-impact scenario (Section 4.6.1.2), which assumes that the impacts on performance measures X_5 through X_8 and X_{14} are at their lowest level as well as a value tradeoff of 1000 million dollars for socioeconomics, the equivalent-consequence evaluations in the last row of Table 4-17 result. Here again, the relative ranking of the sites remains the same.

Table 4-17. Sensitivity analysis of value tradeoffs for socioeconomic impacts[a]

Variation from base case	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Base case ($K_{12} = 5$)	10,173	10,813	11,940	9054	14,492
Double socioeconomic value tradeoff so $K_{12} = 10$	10,273	10,893	12,040	9084	14,507
Low transportation impacts with $K_{12} = 10$	9,541	10,045	11,096	8023	13,404

[a] The numbers in this table represent the total equivalent-consequence impacts in millions of dollars for the base-case ratings and values except as noted in the first column.

4.6.2.4 Sensitivity to risk attitudes about fatalities

To examine the implications of risk attitudes about fatalities, note from the multiattribute utility function (Equation 4-1) and the information in Table 4-7 that an aggregate health-and-safety consequence function C_H is

$$C_H(x_1,\ldots,x_8) = x_1 + x_3 = x_5 + x_7 + 4(x_2 + x_4 + x_6 + x_8), \qquad (4\text{-}4)$$

where C_H is measured in equivalent-consequence impacts, which in this case can also be interpreted as equivalent worker fatalities. Using the ranges from Table 4-6, this function is linearly scaled from the lowest level of no equivalent worker fatalities to 350 equivalent worker fatalities for the highest level. Using the linear fatality function, a lottery that yields a 50-50 chance at no fatalities and a 50-50 chance at 350 fatalities is indifferent to 175 fatalities, which is the expected number of fatalities for the lottery. This is referred to as a risk-neutral attitude.

The risk-averse attitude considered here is when this same lottery is indifferent to 250 fatalities for sure, which is significantly greater than the expected number of fatalities. Since the utility function has been shown to also be a measurable-value function, this risk-averse attitude implies that the relative importance of the first 250 equivalent worker fatalities is exactly equal to the relative importance of the next 100 worker fatalities. In addition, this risk aversion is equivalent to a marginally increasing disutility, meaning that the change from one to two statistical fatalities is more significant than the change from zero to one, and so on.

The risk-prone attitude toward health effects is when a lottery yielding a 50-50 chance at each of 0 or 350 equivalent worker fatalities is indifferent to 100 worker fatalities for sure, much less than the expected number of fatalities. In this case, the relative importance of the first 100 equivalent worker fatalities is equal to that of the next 250 worker fatalities.

Assuming exponential consequence functions fit to the risk-averse and the risk-prone cases and that the change from zero to one statistical worker fatality is as undesirable as an increase of 1 million dollars in cost (i.e., the base-case linear value tradeoff), the aggregate consequence functions for fatalities are

$$C_H(x_1,\ldots,x_8) = -177 + 1271 \exp[0.00563(c_H-350)] \tag{4-5}$$

and

$$C_H(x_1,\ldots,x_8) = 178 - 24.83 \exp[0.00563(350-c_H)], \tag{4-6}$$

where C_H is the equivalent-consequence impact and c_H is the number of equivalent worker fatalities. As shown in Table 4-18, the relative rankings of the sites do not change with either of these risk attitudes.

Table 4-18. Sensitivity to risk attitudes about fatalities[a]

Variation from base case	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Base case (risk neutral)	10,173	10,813	11,940	9054	14,492
Risk averse for fatalities	10,186	10,831	11,961	9077	14,543
Risk prone for fatalities	10,163	10,800	11,925	9038	14,459

[a] The numbers in this table represent the total cost-equivalent impacts in millions of dollars for the base-case ratings, with risk attitudes changed as noted in the first column.

4.6.3 SENSITIVITY ANALYSIS OF THE FORM OF THE UTILITY FUNCTION

It seems useful to analyze whether changing the overall evaluation model to account for a general risk attitude could change the implications of the analysis. To analyze this possibility, one can treat the utility function (Equation 4-1) as a measurable-value function only and place either a risk-averse or a risk-prone attitude on the resulting measurable values. As indicated in Appendix G, a new utility function U for this case can be written

$$U(x_1,\ldots,x_{14}) = A + B \exp[cu(x_1,\ldots,x_{14})], \tag{4-7}$$

where A and B are constants to ensure that U has the same range as u from 0 to 100 and c is a constant indicating the risk attitude. If c is positive, then the attitude is risk prone; if c is negative, a risk-averse attitude is implied. Also, for this sensitivity analysis, it is assumed that there are significant uncertainties in the problem. Specifically, it is assumed that the uncertainty about the impacts of each site can be summarized by a probability distribution yielding either all high estimates or all low estimates from Table 4-6 with a probability of .2 for each. For all base-case estimates from Table 4-6 the probability is assumed to be .6. Equivalent consequences for these situations are shown in Table 4-19.

Table 4-19. Equivalent-consequence impacts of the high-impact, low-impact, and base-case estimates[a]

Impact level	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
High impacts	14,665	15,666	17,200	13,376	20,693
Base case	10,173	10,813	11,940	9,054	14,492
Low impacts	6,185	6,559	7,297	5,312	8,832

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars for performance measures set at the levels indicated.

The results are shown in Table 4-20. In row 1, the equivalent consequences are shown for the base-case analysis. Rows 2 and 3 show the results of the risk-averse situation where there is a penalty on being rated particularly unfavorably on several performance categories simultaneously. For both of these situations, the overall evaluation of the sites remains identical with that in the base case. In rows 4 and 5, risk proneness is considered. Here, there is a willingness to take a chance in order to get all of the performance-measure categories at better levels simultaneously. In these cases, the relative rankings of the sites also remain the same.

Table 4-20. Sensitivity analysis of the overall risk attitude[a]

Variation from base case[b]	Richton Dome	Deaf Smith	Davis Canyon	Yucca Mt.	Hanford
Base case with uncertainty (additive)	10,270	10,940	12,060	9170	14,600
Multiattribute risk aversion	10,400	11,090	12,240	9288	14,850
Strong multiattribute risk aversion	10,620	11,340	12,540	9488	15,280
Multiattribute risk proneness	10,150	10,790	11,890	9054	14,350
Strong multiattribute proneness	9,933	10,550	11,600	8862	13,940

[a]The numbers in this table represent the total equivalent-consequence impacts in millions of dollars for the base-case estimates, with multiattribute risk attitudes changed as noted.

[b]The utility functions of the form in Equation 4-7 were chosen to be consistent with risk attitudes determined by specifying the certainty equivalent (CE) for a lottery corresponding to an equivalent-consequence impact of 5000 with a probability of .5 and an equivalent-consequence impact of 20,000 with a probability of .5. Thus, for instance, the certainty equivalent for the strong-risk-aversion case is that 15,000 is indifferent to an 50-50 chance at each of 5000 and 20,000. For the base-case linear utility function in Equation 4-1, the certainty equivalent for the lottery is 12,500. The certainty equivalents and the utility functions for the five cases are as follows:

Case	CE	Utility function
Base case	12,500	$U = u$
Risk aversion	13,500	$U = 195\ [1 - \exp(-0.00719u)]$
Strong risk aversion	15,000	$U = 117\ [1 - \exp(-0.0193u)]$
Risk proneness	11,500	$U = 95.1\ [\exp(0.00719u - 1)]$
Strong risk proneness	10,000	$U = 17.1\ [\exp(0.0193u - 1)]$

4.6.4 OTHER SENSITIVITY ANALYSES OF THE SET OF OBJECTIVES

Sections 4.1 and 4.2 presented the basis for selecting the objectives and associated performance measures used in this analysis. As explained in Appendix G, other potential objectives were not included because it was felt that their inclusion would not affect the implications of the analysis. Some objectives concerned nonfatal health-and-safety effects (e.g., illness and injuries), and another objective concerned the socioeconomic impacts of the transportation system. The possible implications of including these objectives in the analysis are now considered with a knowledge of the study results.

Nonfatal health-and-safety effects are likely to be highly correlated with the fatalities. Their inclusion would therefore have implications similar to those from a greater value being placed on fatalities. Thus, as illustrated in Table 4-16, the inclusion of nonfatal health-and-safety effects should not affect the implications of the analyses.

The socioeconomic impacts of waste transportation are probably directly related to the total number of miles traveled to deliver waste to the repository and hence to the transportation impacts. These impacts, represented by performance measures X_5 through X_8 and X_{14}, have the same ranking as the overall impacts for the salt sites and Hanford. The socioeconomic impacts of waste transportation to Yucca Mountain could be slightly greater than those associated with the salt sites. Given the overall differences in desirability indicated by the equivalent-consequence impacts in row 11 of Table 4-10, it is unlikely that there would be any change in the ranking of the sites.

4.7 CONCLUSIONS FROM THE PRECLOSURE ANALYSIS

This section summarizes the conclusions for the overall base-case analysis and the sensitivity analyses. Before discussing the overall preclosure analysis, it is useful to review the conclusions with regard to informative performance-measure categories.

Table 4-21 shows the equivalent-consequence impacts and rankings of sites on the performance-measure categories of health and safety, environment and socioeconomics, noncosts, and costs. The ranking on health-and-safety impacts is Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. In terms of equivalent-consequence impacts, the difference between the sites ranked first and fourth is about half the difference between the sites ranked fourth and fifth. The differences in the rankings on health and safety are largely attributable to nonradiological repository-worker fatalities due to accidents and to waste-transportation impacts (radiological and nonradiological) on the public, and to the importance associated with each type of impact (reflected by the value tradeoffs).

Table 4-21. Summary of base-case analysis[a]

Site	Health and safety	Environment and socioeconomics	Noncosts	Costs	Overall equivalent impacts	Base-case utility[b]
Yucca Mountain	83 (4)	71 (2)	154 (2)	8,900 (1)	9,054 (1)	75.7 (1)
Richton Dome	64 (1)	139 (4)	203 (4)	9,970 (2)	10,173 (2)	70.1 (2)
Deaf Smith	74 (2)	119 (3)	193 (3)	10,620 (3)	10,813 (3)	66.9 (3)
Davis Canyon	80 (3)	220 (5)	300 (5)	11,640 (4)	11,940 (4)	61.3 (4)
Hanford	120 (5)	23 (1)	142 (1)	14,350 (5)	14,492 (5)	48.5 (5)

[a] The numbers in the first five columns represent equivalent-consequence impacts in millions of dollars. The numbers in parentheses represent the ranking of the sites.
[b] Calculated for each site with Equation 4-1. In interpreting differences in base-case utility, the reader should recall that one utile is equal in value to 200 million dollars.

The ranking of sites on the aggregate of environmental and socioeconomic performance measures is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. Hanford and Yucca Mountain are most preferable in this category because they have the lowest levels of impact in the component performance measures (i.e., environment and socioeconomics). Deaf Smith has moderate levels of impact in both performance measures and is ranked third. Richton Dome is ranked fourth, mostly because of socioeconomic impacts. Davis Canyon is ranked fifth because it has the highest levels of impact in both performance measures; it is significantly less preferred in the environmental category.

The third column in Table 4-21, labeled "noncosts," aggregates the health-and-safety impacts and the environmental and socioeconomic impacts discussed above. The ranking is Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. It is clear from this ranking that the differences among the sites with regard to health-and-safety impacts are overwhelmed by the differences with regard to the environment and socioeconomics (compare differences in equivalent-consequence impacts in the second and third columns).

The fourth column in Table 4-21 shows the ranking of the sites obtained by combining repository costs and transportation costs. From Table 4-9 (last two rows), it is clear that repository costs dominate the ranking in this performance-measure category.

With these rankings on performance-measure categories in mind, the conclusions for the overall base-case analysis and the sensitivity analyses can be summarized.

The overall equivalent-consequence impacts and ranking of sites for the preclosure period are shown in the fifth column in Table 4-21. The overall preclosure ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. In terms of equivalent-consequence impacts, the difference between Yucca Mountain and Richton is the equivalent of 1119 million dollars, between Richton Dome and Deaf Smith 640 million dollars, between Deaf Smith and Davis Canyon 1127 million dollars, and between Davis Canyon and Hanford 2552 million dollars.

If the equivalent-consequence impacts shown in the fourth column are compared with the total equivalent impacts shown in the fifth column in Table 4-21, the reason for these differences becomes clear. Because the total cost differences among sites are in the billions of dollars and the differences in noncost impacts are equivalent to only 158 million dollars at most (the difference between the first-ranked Hanford site and the fifth-ranked Davis Canyon site in noncost performance-measure category), the differences in costs--especially repository costs--dominate the overall preclosure ranking.

Table 4-21 also shows the overall utility calculated for each site with Equation 4-1. As in Chapter 3 and as explained earlier in this chapter, the utility is expressed on a scale of 0 to 100, where higher utilities are more desirable. This alternative way of expressing preclosure results will facilitate the integration of postclosure and preclosure results in Chapter 5.

The stability of the base-case results was examined by sensitivity analyses involving changes in the level of impacts, in the value judgments, and in the form of the multiattribute utility function itself. Within the ranges estimated for possible impacts, the relative ranking of sites obtained for the base case is totally insensitive to any changes in the level of impacts except for costs. Furthermore, the ranking is insensitive to any reasonable changes in the value judgments or in the form of the utility function.

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Chapter 5

COMPOSITE ANALYSIS

This chapter combines the results of the postclosure and the preclosure multiattribute utility analyses to obtain an overall ranking of the sites. It also explores the sensitivity of that ranking to basic assumptions. Section 5.1 uses the logic of multiattribute utility analysis to formally aggregate the quantitative results. Section 5.2 summarizes the insights obtained from the analysis and presents the initial order of preference for sites for recommendation for characterization.

5.1 FORMAL AGGREGATION OF POSTCLOSURE AND PRECLOSURE RESULTS

Using the logic of the multiattribute utility analysis, the results of the postclosure and preclosure analyses can be formally aggregated. Given the independence assumptions discussed in Appendix G, the composite utility, which quantifies the estimated overall desirability of a site, can be expressed as

$$U_{comp} = k_{pre}U_{pre} + k_{post}[E(U_{post})], \qquad (5\text{-}1)$$

where U_{pre} is the preclosure utility of the site calculated from Equation 4-1, $E(U_{post})$ is the expected postclosure utility of the site calculated from Equation 3-4, and k_{pre} and k_{post} are scaling factors, or weights, that sum to 1. (The expected postclosure utility is the sum of the postclosure utilities estimated for various postclosure scenarios multiplied by the estimated probabilities of the scenarios.)

As explained in Appendix G, it is not easy to interpret the scaling factors, because they depend on the ranges of the performance measures; independent of their ranges, the scaling factors most emphatically cannot be used as indicators of the importance of the respective performance measure. The selection of specific values for the scaling factors requires value tradeoffs between preclosure and postclosure impacts. These value tradeoffs measure how much one is willing to give up on postclosure performance to gain a specific amount on preclosure performance. Before discussing this in detail, it is informative to conduct a sensitivity analysis over the entire range of values for the scaling factors k_{pre} and k_{post}.

Figure 5-1 presents the composite utilities obtained from the results of analyses for the preclosure and the postclosure periods. Figure 5-2 expands that part of the ranges of the scaling factors k_{pre} and k_{post} in which a change in the ranking of sites according to composite utility occurs. The base-case utility for preclosure performance is taken from Table 4-21, and the base-case expected utility for postclosure performance is taken from Table 3-6. The full range of possible relative weightings is considered, from the case where all the weight is given to the postclosure utility ($k_{pre} = 0$ and $k_{post} = 1$) to the case where all the weight is given to the preclosure utility ($k_{pre} = 1$ and $k_{post} = 0$).

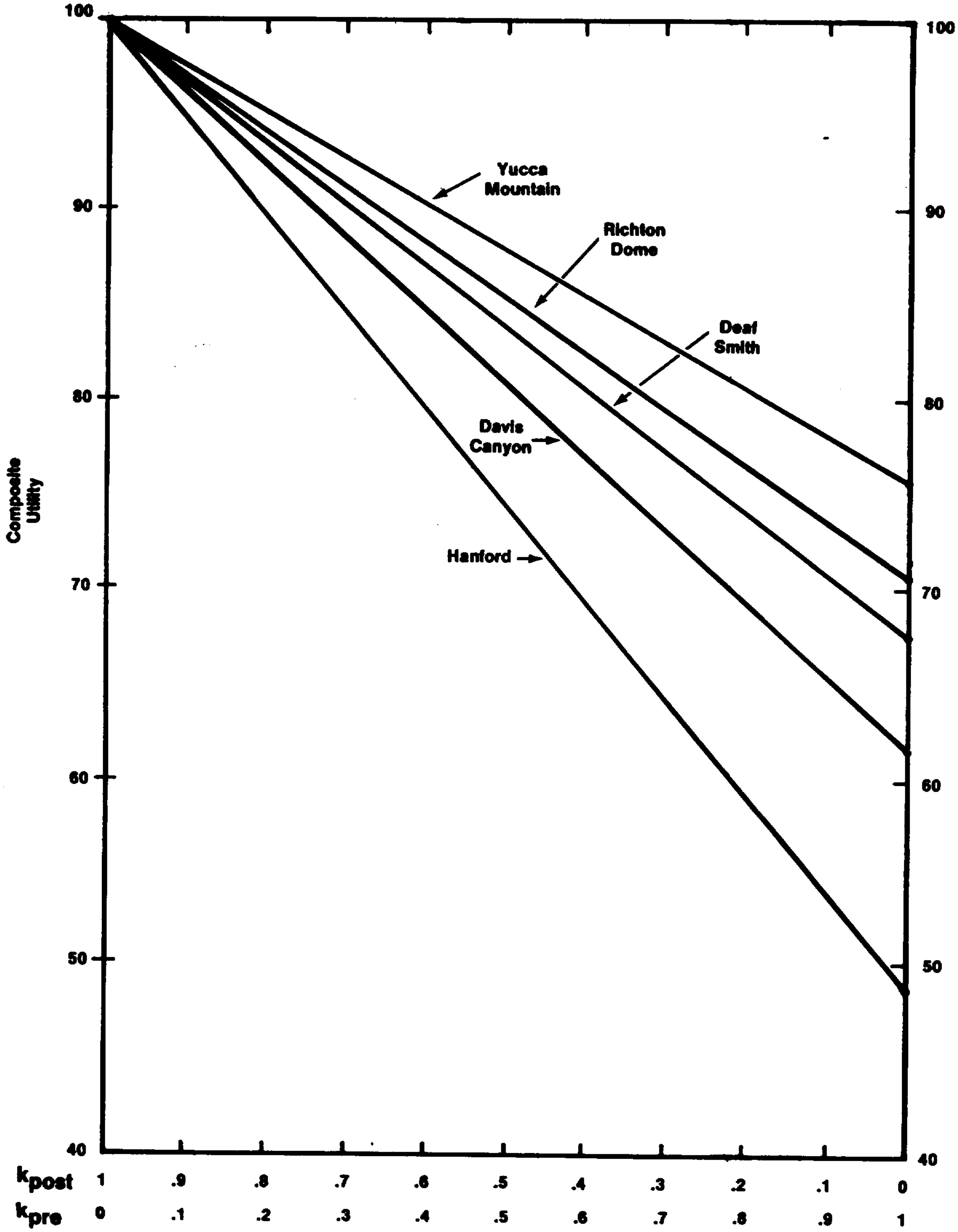

Figure 5-1. Composite utilities of sites for all possible preclosure-postclosure weightings and base-case assumptions.

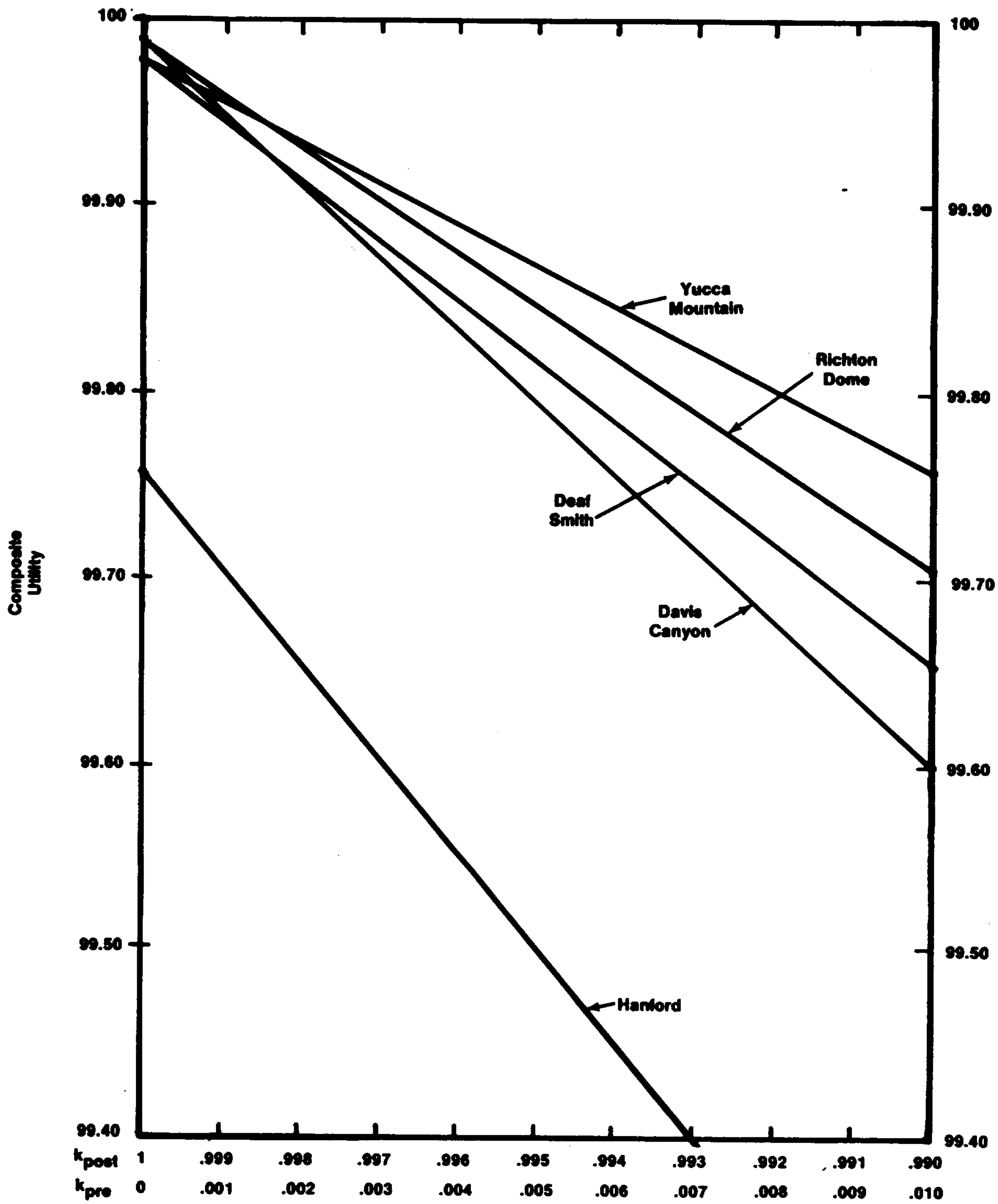

Figure 5-2. Site composite utilities for high postclosure weightings calculated under base-case assumptions.

It is clear from Figures 5-1 and 5-2 that the ranking of the sites remains the same for a wide range of weightings. Over most of the range of possible weightings, the order of overall desirability is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. When an extremely high weight is assigned to the expected postclosure utility (i.e., $k_{post} \geq .998$), the site ranking becomes Davis Canyon and Richton Dome (approximately tied for first), Yucca Mountain and Deaf Smith (approximately tied for second), and Hanford last. Because the differences among the expected postclosure utilities are very small, the differences among the composite utilities for the various sites are also very small when essentially all of the weight is given to the expected postclosure utility.

Figures 5-3 through 5-6 show composite utilities for the five sites when assumptions other than base-case assumptions are used. Figure 5-3 shows the results when optimistic assumptions (high scores and low probabilities for scenarios involving disruptive events and unexpected features) are used for the postclosure analysis and optimistic assumptions (low impact levels) are used for the preclosure analysis. Figure 5-4 shows the results when pessimistic assumptions (low scores and high probabilities for scenarios involving disruptive events and unexpected features) are used for the postclosure analysis and pessimistic assumptions (high impact levels) are used for the preclosure analysis. Figures 5-5 and 5-6 show the mixed cases in which optimistic or pessimistic assumptions are adopted for the postclosure analysis and the reverse assumption is adopted for the preclosure analysis.

Although the values of the scaling factors at which the overall ranking changes depend on whether base-case, pessimistic, or optimistic assumptions are used, certain patterns are clear and stable under a wide range of assumptions. The Hanford site is in all cases ranked fifth (i.e., it has the lowest composite utility), regardless of the relative weight assigned to the preclosure and the postclosure utilities. This is so because it is ranked fifth for all sets of assumptions in both the preclosure and the postclosure analyses. The relative ranking among the salt sites (Richton Dome, Deaf Smith, Davis Canyon) remains the same regardless of whether base-case, optimistic, or pessimistic assumptions are used unless a very high weight is assigned to the postclosure utility, in which case the composite utilities of the salt sites are nearly equal. Yucca Mountain is the site whose ranking is most affected by the choice of pessimistic, base-case, or optimistic assumptions. Under pessimistic assumptions for postclosure performance, Yucca Mountain receives a lower expected postclosure utility because of the possibility of relatively large radionuclide releases in a scenario due to unexpected features. If pessimistic assumptions are used for postclosure performance, then Yucca Mountain is ranked first only if the postclosure scaling factor k_{post} is less than about .2; it is in the three top-ranked sites only if k_{post} is less than about .35. Under base-case or optimistic assumptions for postclosure performance, Yucca Mountain is ranked first across nearly the entire ranges of k_{pre} and k_{post}.

In view of the dominant effect of costs on the preclosure ranking of sites and the dominance of the preclosure utility over the postclosure utility in determining the overall ranking based on the composite utility, it is of interest to investigate what the overall rank order of the sites would be if differences in costs were not considered. Figure 5-7 shows the utilities calcu-

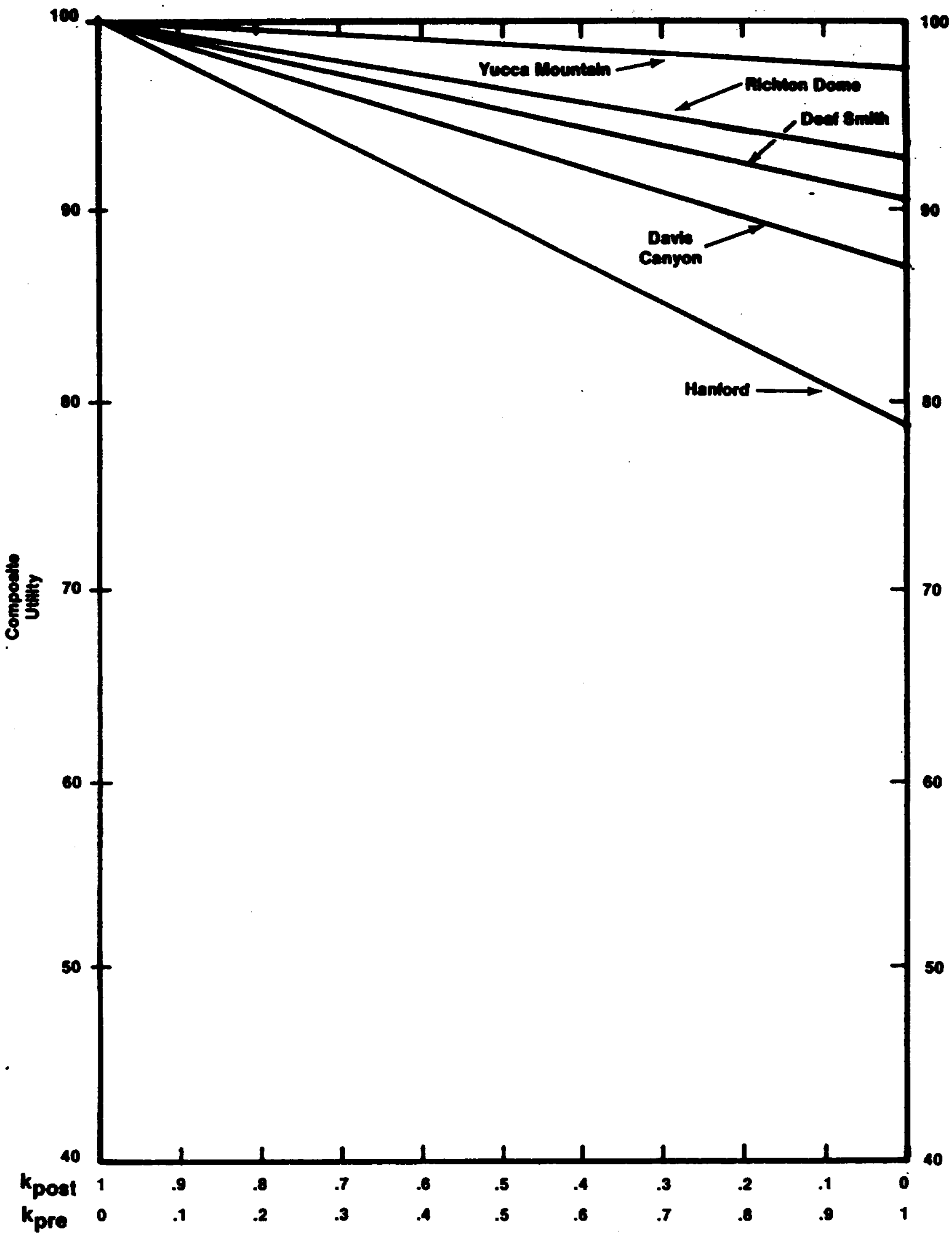

Figure 5-3. Site composite utilities calculated under optimistic assumptions for postclosure and preclosure.

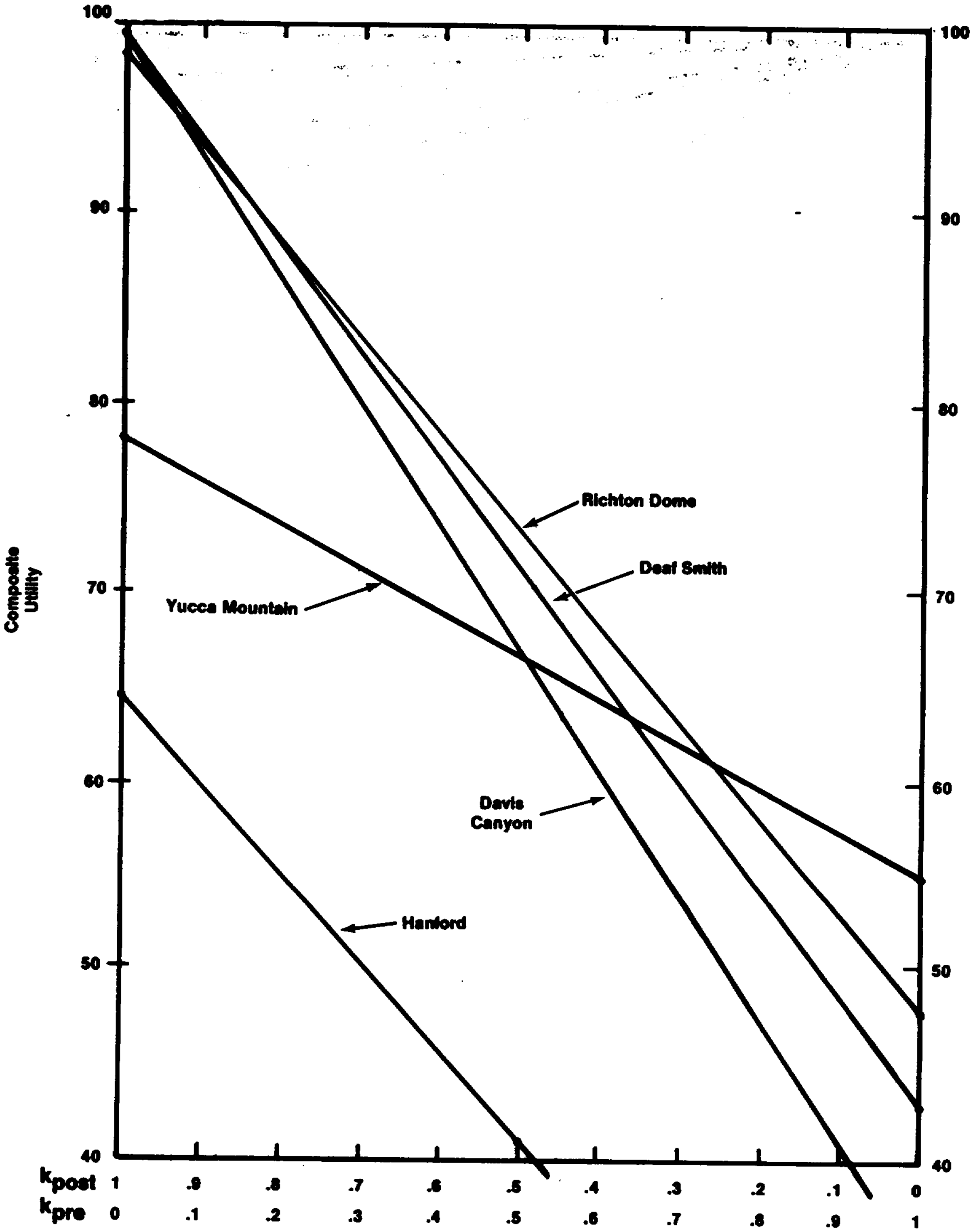

Figure 5-4. Site composite utilities calculated under pessimistic assumptions for postclosure and preclosure.

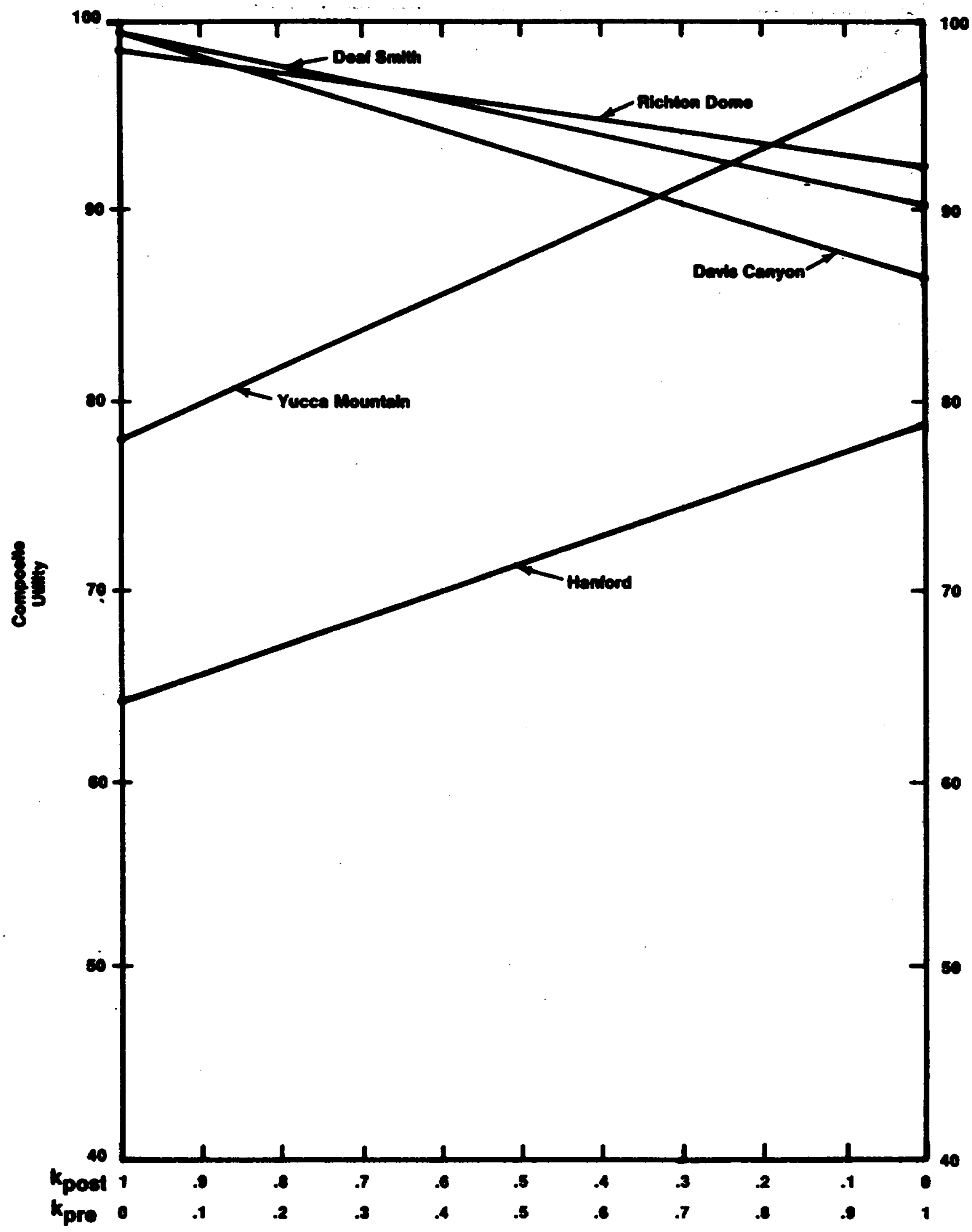

Figure 5-5. Site composite utilities calculated under pessimistic assumptions for postclosure and optimistic assumptions for preclosure.

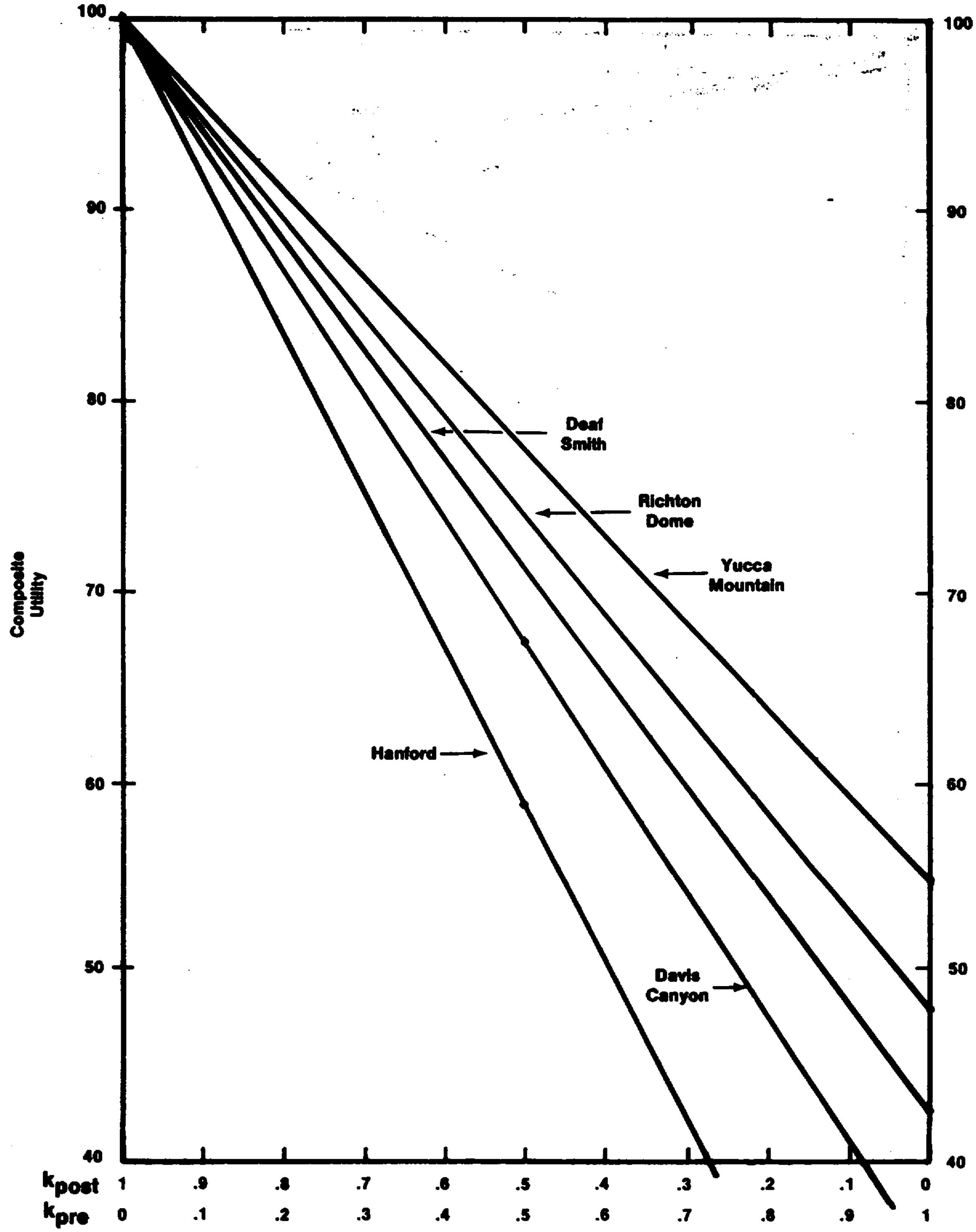

Figure 5-6. Site composite utilities calculated under optimistic assumptions for postclosure and pessimistic assumptions for preclosure.

lated for each site when repository and transportation costs (X_{13} and X_{14}) are identical for all sites and are set at the lowest levels deemed possible for the nominated sites. In this case, preclosure differences no longer dominate the overall rank order, and the ranking depends critically on the scaling factors k_{pre} and k_{post}. If k_{post} is less than about .57, the three-top ranked sites are Yucca Mountain, Deaf Smith, and Hanford. If a weight higher than .57 is assigned to the postclosure utility, the three top-ranked sites are Yucca Mountain, Deaf Smith, and Richton Dome. The rankings in this case are the rankings that would be obtained if only health-and-safety, socioeconomic, and environmental objectives were considered.

Figure 5-8 shows the results obtained when socioeconomic impacts, environmental impacts, and costs are assumed to be identical for all sites. Specifically, all sites are assumed to have no socioeconomic and environmental impacts, and the repository and waste-transportation costs for all sites are set at the lowest level deemed possible for the nominated sites. Thus, only health-and-safety objectives are considered. In this case, the three top-ranked sites are Richton, Deaf Smith, and Davis Canyon, regardless of the preclosure-to-postclosure weighting. From Figures 5-7 and 5-8 it can be seen that costs account for the major differences in composite utilities. When costs or costs plus socioeconomic and environmental impacts are not considered, the composite utilities of the sites are comparable, indicating that the sites are nearly equal in desirability, regardless of the values assigned to the scaling factors k_{pre} and k_{post}.

Because of the sensitivity of the rankings to the relative values of k_{pre} and k_{post}, it is of interest to consider the reasonableness of different numerical values. As in the case with the scaling factors used in Chapters 3 and 4, the scaling factors k_{pre} and k_{post} must be based on a value judgment, in this case a value tradeoff between postclosure performance and preclosure performance. The value of k_{pre} determines the increase in composite utility that would result from increasing the preclosure utility by one utile--that is, by one unit. An increase of one utile in the preclosure utility might be produced in a variety of ways. For example, from Chapter 4, a one-utile increase in the preclosure utility would be produced by a $200 million decrease in repository costs, by a reduction of 50 statistical fatalities in the public, or by a $100 million decrease in costs coupled with a reduction of 25 statistical fatalities in the public. Similarly, k_{post} determines the increase in composite utility that would result from increasing the postclosure utility by one utile. According to Chapter 3, a one-utile increase in the postclosure utility would be produced if the cumulative radionuclide releases were decreased by an amount equal to one one-hundredth of the limits allowed by the EPA standards for each 10,000-year interval in 100,000 years. A decision to set the scaling-factor values at $k_{pre} = k_{post} = .5$, for example, would be equivalent to the value judgment that a preclosure difference of $100 million in repository costs and 25 statistical fatalities is about as significant as a postclosure release difference of one one-hundredth of the EPA limits during each 10,000-year interval for 100,000 years.

To better judge whether particular numerical values for k_{pre} and k_{post} are reasonable, it is helpful to select convenient measures for summarizing preclosure and postclosure performance and to consider whether the tradeoffs between these measures are reasonable. This tradeoff is most

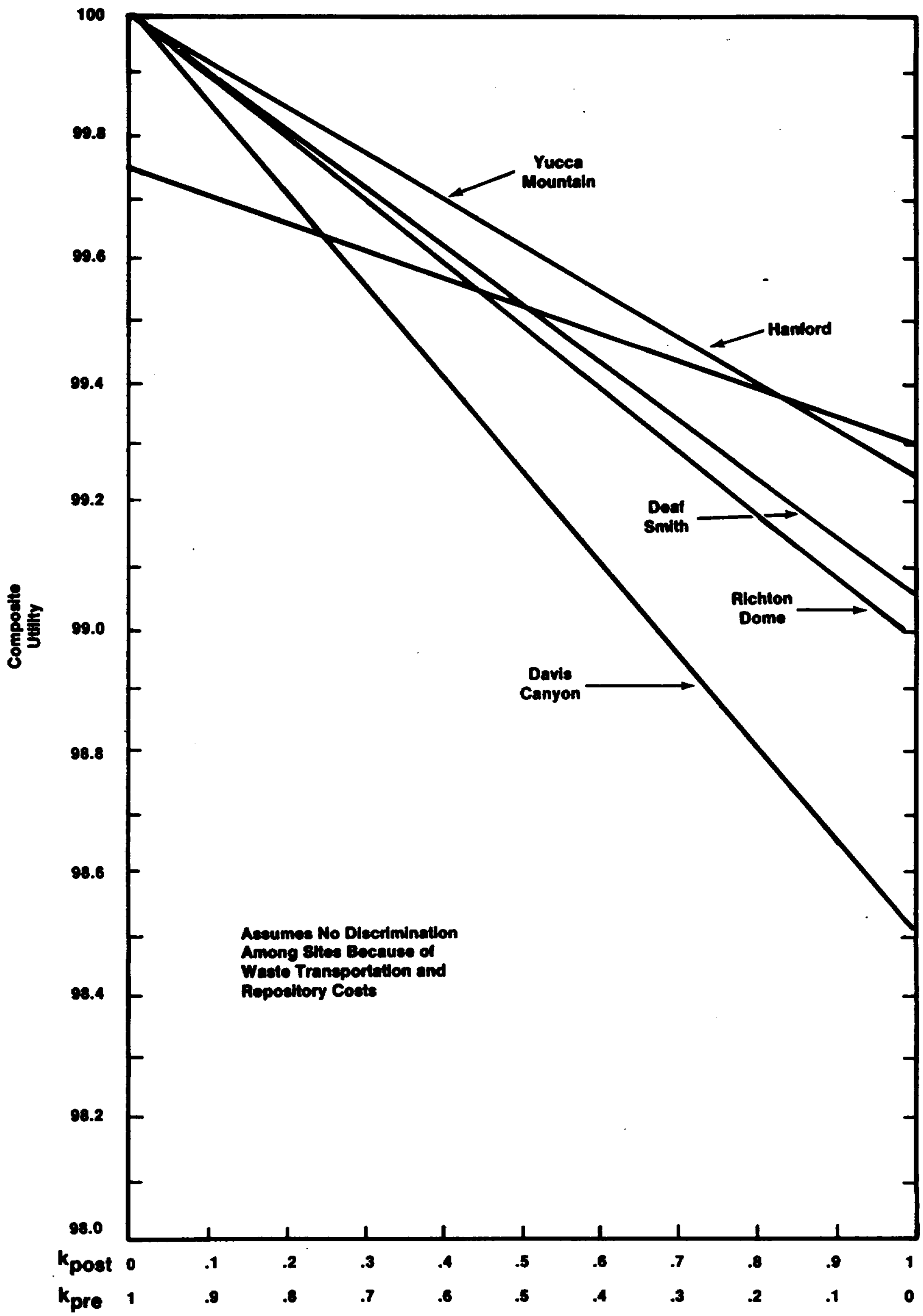

Figure 5-7. Composite utilities of sites as a function of preclosure-to-postclosure weighting for base-case conditions, assuming identical waste-transportation and repository costs for all sites.

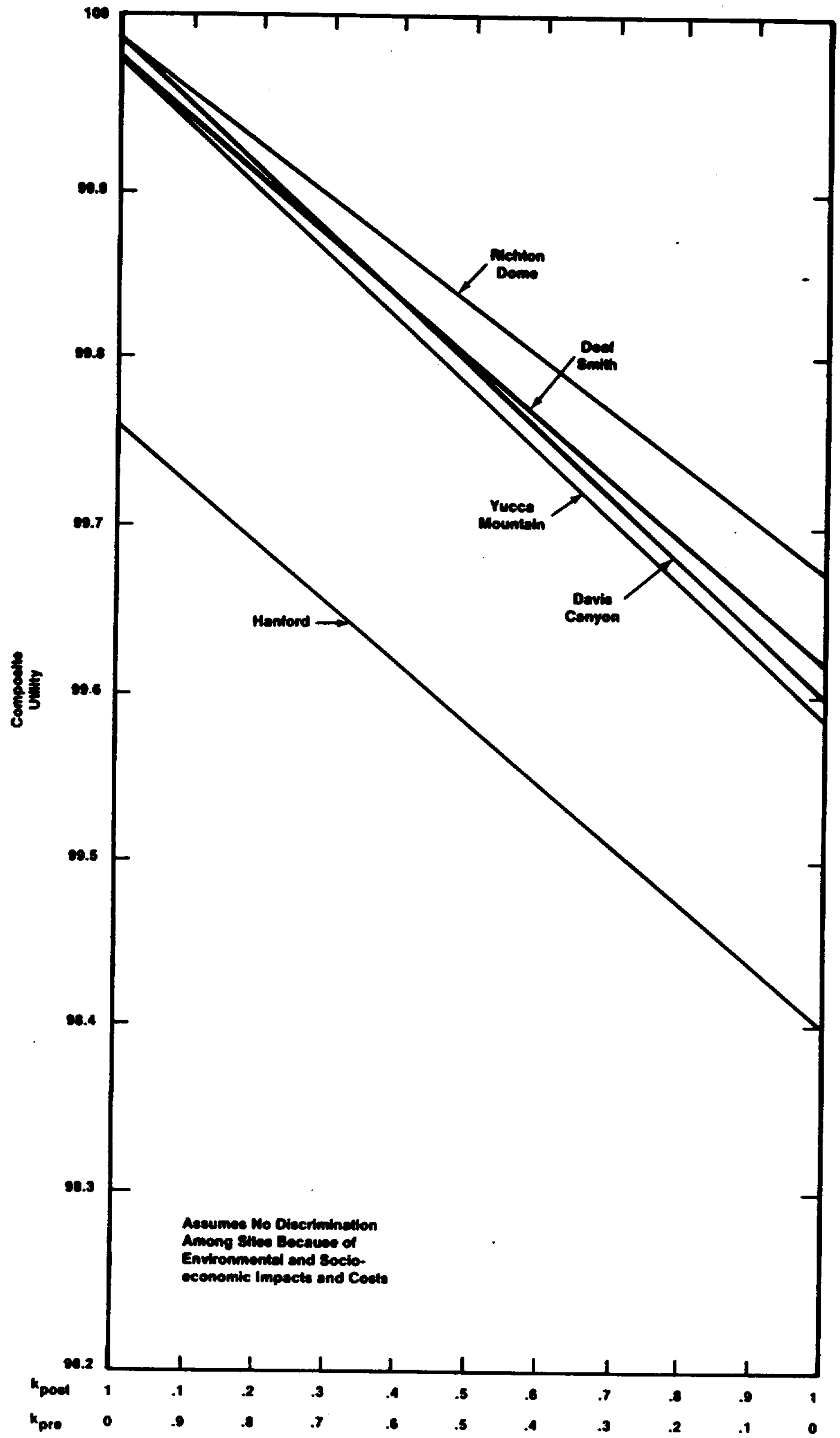

Figure 5-8. Composite utilities of sites as a function of preclosure-to-postclosure weighting for base-case conditions, assuming no environmental and socioeconomic impacts and identical waste-transportation and repository costs for all sites.

conveniently considered in terms of preclosure and postclosure radiological safety. Specifically, if the preclosure radiological safety is expressed in terms of cancer fatalities and the postclosure radiological safety is expressed in terms of cumulative radionuclide releases, the value tradeoff can be expressed as the postclosure radionuclide releases y (occurring in the first 10,000 years after repository closure) that would be just as undesirable as 10 additional preclosure cancer fatalities. Table 5-1 shows the values for the scaling factors k_{pre} and k_{post} that correspond to several different tradeoffs. These values for the scaling factors were calculated as follows:

1. The preclosure-utility decrease from an additional 10 cancer fatalities in the public is found from Equation 4-1 to be (1/200)(4)(10) = 0.2.

2. The postclosure-utility decrease from an increase in radionuclide releases y during the first 10,000 years is found from Equation 3-3 to be (0.526)(100)(y) = 52.6y, where y is expressed as a fraction of the EPA limits.

Table 5-1. Value tradeoffs between preclosure radiological health effects and postclosure radionuclide releases implied by various values of the scaling factors k_{pre} and k_{post}

k_{pre}	[b]k_{post}	Postclosure release y deemed as undesirable as 10 preclosure fatalities[a] (fraction of EPA limits[c])
1.0	0.0	—
0.99	0.01	0.38
0.9	0.1	0.03
0.8	0.2	0.02
0.7	0.3	0.01
0.6	0.4	0.006
0.5	0.5	0.004
0.4	0.6	0.003
0.3	0.7	0.002
0.2	0.8	0.001
0.1	0.9	0.0004
0.01	0.99	0.00004
0.0	1.0	—

[a]Preclosure cancer fatalities incurred by the public from the repository.
[b]Since the scaling factors sum to 1, $k_{post} = 1 - k_{pre}$.
[c]Primary containment requirements of 10 CFR Part 191, Subpart B.

3. The postclosure-versus-preclosure tradeoff implies that each of the above changes produces the same decrease in the composite utility. From Equation 5-1, therefore,

$$k_{pre}(0.2) = k_{post}(52.6y),$$

which implies that

$$y = 0.0038(k_{pre}/k_{post}).$$

Table 5-1 shows, for various values of the scaling factors, the postclosure radionuclide releases y that would be regarded as undesirable as 10 preclosure cancer fatalities in the public.

The reasonableness of the various value tradeoffs in Table 5-1 can be seen more easily if a relationship is assumed between postclosure releases and postclosure health effects. As noted in Chapter 3, in 40 CFR Part 191 the U.S. Environmental Protection Agency adopted the assumption that, for each 1000 metric tons of heavy metal (MTHM), cumulative releases at the level the EPA limits would result in 10 deaths from cancer. Because a repository at any of the nominated sites is assumed to accept 70,000 MTHM, releases at the level of the EPA limits would produce approximately 700 cancer fatalities in 10,000 years.

Table 5-2 shows the tradeoff between preclosure and postclosure cancer fatalities that is implied by various values of the scaling factors if the radionuclide releases shown in Table 5-1 are converted to postclosure fatalities under the EPA assumption. Because the EPA relationship between postclosure releases and cancer fatalities probably overestimates the fatalities, the implied value tradeoff is likely to be a lower bound on the relative significance of postclosure fatalities. It is noted that the selection of scaling-factor values that imply a willingness to trade off a great many postclosure fatalities (i.e., values at the top portion of Table 5-2) may be inappropriate in view of the requirement in the DOE siting guidelines that postclosure considerations be given greater importance than preclosure considerations.

As can be seen from Figures 5-1, 5-2, 5-3, and 5-6, the composite utilities imply that the overall site ranking is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford for all postclosure weights equal to or less than .99, provided that the postclosure performance is assumed to be at the base-case level or optimistic (regardless of the preclosure assumptions). Values of k_{post} greater than .99 would, according to Table 5-2, imply a willingness to accept more than 350 preclosure cancer fatalities to avoid 1 postclosure cancer fatality. If pessimistic assumptions are used for postclosure performance, Yucca Mountain falls out as the overall preferred site when the implied value tradeoff between postclosure and preclosure cancer fatalities is approximately 1:1 (i.e., k_{post} = .21). It drops from among the three top-ranked sites when, under pessimistic assumptions, this implied value tradeoff is such that approximately two preclosure fatalities would be accepted to avoid one postclosure fatality (i.e., k_{post} = .35).

Table 5-2. Value tradeoffs between preclosure and postclosure radiological health effects implied by various values of the scaling factors k_{pre} and k_{post}

k_{pre}	[a] k_{post}	Implied value tradeoff between preclosure and postclosure cancer fatalities
1.0	0.0	—
0.99	0.01	1:26
0.9	0.1	1:2.4
0.8	0.2	1:1.1
0.79	0.21	1:1
0.7	0.3	1.6:1
0.6	0.4	2.5:1
0.5	0.5	3.8:1
0.4	0.6	5.6:1
0.3	0.7	8.8:1
0.26	0.74	10:1
0.2	0.8	15:1
0.1	0.9	34:1
0.01	0.99	372:1
0.0	1.0	—

[a] Since the scaling factors sum to 1, $k_{post} = 1 - k_{pre}$.

In interpreting the significance of computed differences in composite utilities, it is necessary to consider the values of the scaling factors k_{pre} and k_{post}. For any given values of these scaling factors, the significance of a given difference in utilities can be deduced from the meaning of preclosure and postclosure utilities. For example, suppose that values of .5 were judged reasonable for k_{pre} and k_{post}, and suppose that two sites had composite utilities that differed by 0.1 utile. A decrease of one utile in postclosure utility corresponds to a decrease in desirability comparable to that produced by an increase in radionuclide releases equal to one one-hundredth of the EPA limits, assuming that these releases occur during each 10,000-year interval for 100,000 years. A decrease of one utile in preclosure utility corresponds to a decrease in desirability comparable to that produced by an additional $200 million in costs (equivalent to, for example, an additional 50 preclosure statistical radiological fatalities suffered by the public). Thus, given the preclosure and postclosure weights selected above, a difference of 0.1 utile in the composite utilities corresponds to a difference in desirability comparable to that of decreasing postclosure releases by one one-thousandth of the EPA limits and simultaneously decreasing by five the number of preclosure radiological fatalities in the public. Alternatively, the difference in composite utilities corresponds to a difference in desirability comparable to that of decreasing preclosure radiological fatalities in the public by 10 and leaving postclosure radionuclide releases unchanged.

5.2 INITIAL ORDER OF PREFERENCE FOR SITES FOR RECOMMENDATION FOR CHARACTERIZATION

As indicated in Chapters 1 and 2, the purpose of the decision-aiding methodology is to provide insights as to the comparative advantages and disadvantages of the five sites and, in so doing, to determine an initial order of preference for sites for recommendation for characterization. With reference to the postclosure, preclosure, and composite analyses of sites presented in this report, the major insights derived from the multiattribute utility analysis are summarized below.

Postclosure analysis

- All five sites appear capable of providing exceptionally good radiological protection for future populations for at least 100,000 years after closure.

- The Davis Canyon, Deaf Smith, Richton Dome, and Yucca Mountain sites appear to be virtually indistinguishable in terms of the expected postclosure performance. The Hanford site is just discernibly less favorable than the other four sites, but its performance is still far above the threshold of acceptability established by the EPA. It is noted that the primary containment requirements of the EPA--the criterion of acceptability used here--provide a very stringent standard for protecting public health and safety: the risk to the public is not to exceed the risks that would have existed if the uranium ore that was the source of the waste had not been mined to begin with.

- The confidence in the performance of the three salt sites (Davis Canyon, Deaf Smith, and Richton Dome) is exceptionally high, and it is higher than that for the nonsalt sites (Hanford and Yucca Mountain).

- The overall postclosure ranking of Davis Canyon, Richton Dome, Deaf Smith, Yucca Mountain, and Hanford is stable over a wide range of sensitivity analyses.

Preclosure analysis

- With regard to preclosure health and safety, the site rankings are Richton Dome, Deaf Smith, Davis Canyon, Yucca Mountain, and Hanford. The differences among the sites are largely attributable to waste transportation and to nonradiological repository-worker fatalities due to accidents.

- With regard to environmental and socioeconomic impacts, the site rankings are Hanford, Yucca Mountain, Deaf Smith, Richton Dome, and Davis Canyon. The difference between sites is greater than the difference on health-and-safety impacts. However, this difference is relatively small in comparison with differences in total costs.

- With regard to total costs, the site rankings are Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. The difference between the most favorable site and the least favorable site is equal to 4380 million (4.38 billion) dollars.

- Considering all preclosure impacts, the overall ranking of sites is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. This ranking is stable over a wide range of sensitivity analyses.

- The overall preclosure ranking is mainly attributable to the large differences among sites in total costs. The fact that cost is the major preclosure discriminator can be explained by the screening process that led to the nominated sites (see Chapter 1). Because the criteria used in screening were concerned with health and safety and the environment, but not with costs, sites expected to perform poorly on objectives other than costs have already been screened out.

Composite analysis

- Because the differences among sites in postclosure performance are very small and the differences in preclosure performance are relatively large, the overall composite results are largely a reflection of the preclosure impacts and thus of costs.

- The composite overall ranking of sites is basically insensitive to the relative values of the scaling factors k_{post} and k_{pre}.

- The composite overall ranking under a wide range of assumptions is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford.

It follows, therefore, that the overall ranking of sites is Yucca Mountain, Richton Dome, Deaf Smith, Davis Canyon, and Hanford. This ranking is stable except for the most extreme assumptions about postclosure performance combined with the most extreme weightings of postclosure performance versus preclosure performance.

As noted above, this overall ranking of sites is largely a reflection of differences in costs. This dependence on costs was recognized by the Board on Radioactive Waste Management of the National Academy of Sciences in its comments on the application of the methodology (see attachment to Appendix H, letter dated April 10, 1986, p. 4): "On the basis of the Board's review of the application to a single site, it appears that the expected total repository and transportation costs will have a major, if not controlling, effect on the rankings under pre-closure factors." As shown in Figure 5-7, when repository and transportation costs are not discriminating and postclosure performance is weighted up to about .57, the three top-ranked sites are Yucca Mountain, Deaf Smith, and Hanford. When higher weight is given to postclosure performance, the three top-ranked sites are Yucca Mountain, Deaf Smith, and Richton.

In view of the requirements of the siting guidelines that costs be among the factors given the least importance among preclosure considerations, the above rankings must be carefully considered. The need to consider carefully the results obtained with the methodology was also recognized by the Board in the above-cited letter: "This recognition of the heavy dependence on cost reinforces the Board's judgment that the principal usefulness of the multi-attribute utility method is to illuminate the factors involved in a decision, rather than to make the decision itself." Furthermore, as explained in Section 2.1, the site-recommendation decision is analogous to a portfolio-selection problem because the DOE is not choosing a single site for repository development; rather, the DOE must choose, from a suite of five well-qualified sites, three sites for characterization. Combinations of three sites possess properties that cannot be attributed to individual sites, such as diversity of geohydrologic settings and rock types.

GLOSSARY OF TERMS

Accessible environment	The atmosphere, the land surface, surface water, oceans, and the portion of the lithosphere that is outside the controlled area.
Act	The Nuclear Waste Policy Act of 1982.
Active fault	A fault along which there is recurrent movement, which is usually indicated by small, periodic displacements or seismic activity.
Active institutional controls	(1) Controlling access to a disposal site by any means other than passive institutional controls; (2) performing maintenance operations or remedial actions at a site; (3) controlling or cleaning up releases from a site; or (4) monitoring parameters related to disposal system performance.
Affected area	Either the area of socioeconomic impact or the area of environmental impact, each of which will vary in size among potential repository sites.
Affected Indian Tribe	Any Indian (1) within whose reservation boundaries a repository for radioactive waste is proposed to be located or (2) whose federally defined possessory or usage rights to other lands outside the reservation boundaries arising out of congressionally ratified treaties may be substantially and adversely affected by the locating of such a facility: provided that the Secretary of the Interior finds, upon the petition of the appropriate governmental officials to the Tribe, that such effects are both substantial and adverse to the Tribe.
Aquifer	A formation, a group of formations, or a part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.
Barrier	Any material or structure that prevents or substantially delays the movement of water or radionuclides.
Basalt	A dark to medium dark igneous rock usually formed from lava flows and composed chiefly of calcic plagioclase and clinopyroxene in a glassy or fine-grained ground mass.
Candidate site	An area, within a geohydrologic setting, that is recommended by the Secretary of Energy under

Section 112 of the Act for site characterization, approved by the President under Section 112 of the Act for characterization, or undergoing site characterization under Section 113 of the Act.

Canister	A metal vessel for consolidated spent fuel or solidified high-level waste. Before emplacement in the repository, the canister will be encapsulated in a disposal container.
Cenozoic	The latest of the eras into which geologic time, as recorded by the stratified rocks of the earth's crust, is divided; this era is considered to have begun about 65 million years ago.
Certain equivalent	That certain value, expressed in terms of the units used to measure an uncertain impact, that a decisionmaker is just willing to accept in lieu of the uncertain impact.
Closure	Final backfilling of the remaining open operational areas of the underground facility and boreholes after the termination of waste emplacement, culminating in the sealing of shafts.
Containment	The confinement of radioactive waste within a designated boundary.
Container	Synonym for the metal envelope in the waste package that provides the primary containment function of the waste package and is designed to meet the containment requirements of 10 CFR Part 60.
Controlled area	(1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location.
Cumulative releases of radionuclides	The total number of curies of radionuclides entering the accessible environment in any 10,000-year period, normalized on the basis of radiotoxicity in accordance with 40 CFR Part 191. The peak cumulative release of radionuclides refers to the 10,000-year period during which any such release attains its maximum predicted value.
Darcian flow	Flow of fluids that is described by a numerical formulation of Darcy's law.

Decommissioning	The permanent removal from service of surface facilities and components necessary for preclosure operations only, after repository closure, in accordance with regulatory requirements and environmental policies.
Disposal	The emplacement in a repository of high-level radioactive waste, spent nuclear fuel, or other highly radioactive material with no foreseeable intent of recovery, whether or not such emplacement permits the recovery of such waste, and the isolation of such waste from the accessible environment.
Disqualifying condition	A condition that, if present at a site, would eliminate that site from further consideration.
Disutility	A quantitative measure of undesirability.
DOE	The U.S. Department of Energy.
dome	A diapiric or piercement structure with a central plug that has risen through the enclosing sediments from a deep mother bed of salt.
EA	Environmental assessment.
Effective porosity	The amount of interconnected pore space and fracture openings available for the transmission of fluids, expressed as the ratio of the volume of interconnected pores and openings to the volume of rock.
Engineered-barrier system	The manmade components of a disposal system designed to prevent the release of radionuclides from the underground facility or into the geohydrologic setting. Such term includes the radioactive-waste form, radioactive-waste canisters, materials placed over and around such canisters, any other components of the waste package, and barriers used to seal penetrations in and into the underground facility.
Environmental assessment	The document required by Section 112(b)(E) of the Nuclear Waste Policy Act of 1982.
EPA	The U.S. Environmental Protection Agency.
EPA limits	The radionuclide release limits for the containment requirements (cumulative releases to the accessible environment for 10,000 years after disposal) as specified by Table 1 and Notes 1 through 6 of Appendix A of 40 CFR Part 191.

EPA standard	Part 191 of Title 40 of the Code of Federal Regulations--Environmental Standards for the Management and Disposal of Spent Fuel, High-Level and Transuranic Radioactive Wastes.
Equivalent releases	A release rate per 10,000-year interval (at a given site) that, if it were to occur for 100,000 years, the site would have the same expected utility as that calculated for the given site. The equivalent releases for a site are the certain equivalent of the uncertain releases from that site (see "certain equivalent").
Expected releases	Expected value of releases.
Equivalent-consequence impact	As used in this report, a monetary equivalent of an adverse impact expressed in millions of dollars.
Expected repository performance	The manner in which the repository is predicted to function, considering those conditions, processes, and events that are likely to prevail or may occur during the time period of interest.
Expected utility	Expected value of an uncertain utility.
Expected value	A summary measure for an uncertain numerical variable obtained by weighting all possible outcomes by their probabilities and summing.
Facility	Any structure, system, or system component, including engineered barriers, created by the DOE to meet repository-performance or functional objectives.
Fault	A fracture or a zone of fractures along which there has been displacement of the sides relative to one another and parallel to the fracture or zone of fractures.
Faulting	The process of fracturing and displacement that produces a fault.
Favorable condition	A condition that, though not necessary to qualify a site, is presumed, if present, to enhance confidence that the qualifying condition of a particular guideline can be met.
Gassy mine	Underground operation in which the content of noxious or explosive gasses has been shown to exceed levels specified in 30 CFR Part 57 by the Mine Safety and Health Administration.
Geohydrologic setting	The system of geohydrologic units that is located within a given geologic setting.

Geohydrologic system	The geohydrologic units within a geologic setting, including any recharge, discharge, interconnections between units, and any natural or man-induced processes or events that could affect ground-water flow within or among those units.
Geohydrologic unit	An aquifer, a confining unit, or a combination of aquifers and confining units comprising a framework for a reasonably distinct geohydrologic system.
Geologic repository	A system, requiring licensing by the Nuclear Regulatory Commission, that is intended to be used, or may be used, for the disposal of radioactive waste in excavated geologic media. A geologic repository includes (1) the geologic-repository operations area and (2) the portion of the geologic setting that provides isolation of the radioactive waste and is located within the controlled area.
Geologic setting	The geologic, hydrologic, and geochemical systems of the region in which a geologic-repository operations area is or may be located.
Geomorphic processes	Geologic processes that are responsible for the general configuration of the earth's surface, including the development of present land forms and their relationships to underlying structures, and are responsible for the geologic changes recorded by these surface features.
Great Basin	A subdivision of the Basin and Range province, located in southern Nevada in a broad desert region. The Yucca Mountain site is in the Great Basin.
Ground water	All subsurface water as distinct from surface water.
Ground-water flux	The rate of ground-water flow per unit area of porous or fractured media measured perpendicular to the direction of flow.
Ground-water sources	Aquifers that have been or could be economically and technologically developed as sources of water in the foreseeable future.
Ground-water-travel time	The time required for a unit volume of ground water to travel between two locations. The travel time is the length of the flow path divided by the velocity, where velocity is the average ground-water flux passing through the

cross-sectional area of the geologic medium through which flow occurs, perpendicular to the flow direction, divided by the effective porosity along the flow path. If discrete segments of the flow path have different hydrologic properties, the total travel time will be the sum of the travel times for each discrete segment.

Guidelines	Part 960 of Title 10 of the Code of Federal Regulations--General Guidelines for the Recommendation of Sites for the Nuclear Waste Repositories.
Hanford Site	A DOE reservation covering nearly 600 square miles in south-central Washington. A portion of this reservation has been identified as a potentially acceptable site in basalt and is called the "Hanford site" or the "reference repository location."
Heavy metal	All uranium, plutonium, or thorium placed into a nuclear reactor.
High-level waste	The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determined by rule to require permanent isolation.
Host rock	The geologic medium in which the waste is emplaced, specifically the geologic materials that directly encompass and are in close proximity to the underground facility.
Hydraulic conductivity	The volume of water that will move through a medium in a unit of time under a unit hydraulic gradient through a unit area measured perpendicular to the direction of flow.
Hydraulic gradient	A change in the static pressure of ground water, expressed in terms of the height of water above a datum, per unit of distance in a given direction.
Hydrologic process	Any hydrologic phenomenon that exhibits a continuous change in time, whether slow or rapid.
Hydrologic properties	Those properties of a rock that govern the entrance of water and the capacity to hold, transmit, and deliver water, such as porosity,

effective porosity, specific retention, permeability, and the directions of maximum and minimum permeabilities.

Igneous activity	The emplacement (intrusion) of molten rock material (magma) into material in the Earth's crust or the explosion (extrusion) of such material onto the earth's surface or into its atmosphere or surface water.
Impact level	An indication of the degree of impact.
Indifferent	Equally preferable; that is, such that there is no preference between two or more choices.
Influence diagram	A graphic diagram illustrating the various factors that influence the degree to which an objective is met and the relationships among such factors.
Isolation	Inhibiting the transport of radioactive material so that the amounts and concentrations of this material entering the accessible environment will be kept within prescribed limits.
Judgmental probability	A quantitative expression of likelihood based on personal belief and obeying the axioms of probability theory. Judgmental probabilities are equal to objective probabilities acceptable to the assessor for a substitute gamble.
Lithosphere	The solid part of the earth, including any ground water contained within it.
Lottery	A mutually exclusive and collectively exhaustive set of possible consequences and the probability of each consequence.
Maximally exposed individual	A hypothetical person who is exposed to a release of radioactivity in such a way that he receives the maximum possible individual radiation dose or dose commitment. For instance, if the release is a puff of contaminated air, the maximally exposed individual is a person at the point of the largest ground-level concentration and stays there during the whole time the contaminated-air cloud remains above.
Member of the public	Any individual who is not engaged in operations involving the management, storage, and disposal of radioactive waste. A worker so engaged is a member of the public except when on duty at the geologic-repository operations area.

Millirem	1 millirem is 1/1,000 of a rem.
Mitigation	(1) Avoiding the impact altogether by not taking a certain action or parts of an action; (2) minimizing impacts by limiting the degree or magnitude of the action and its implementation; (3) rectifying the impact by repairing, rehabilitating, or restoring the affected environment; (4) reducing or eliminating the impact over time by preservation and maintenance operations during the life of the action; or (5) compensating for the impact by replacing or providing substitute resources or environments.
Model	A conceptual description and the associated mathematical representation of a system, subsystem, component, or condition that is used to predict changes from a baseline state as a function of internal and/or external stimuli and as a function of time and space.
MTHM	Metric tons of heavy metal.
NRC	The U.S. Nuclear Regulatory Commission.
Nevada Test Site	An area in Clark and Nye Counties in southern Nevada; it is dedicated to the underground testing of nuclear weapons.
Paradox Basin	A 25,900-square-kilometer (10,000-square-mile) area in southeastern Utah and southwestern Colorado; it is underlain by bedded salt and a series of salt-core anticlines. The Davis Canyon site is in the Paradox Basin.
Pasco Basin	A structural and topographic basin in the western Columbia Plateau. The Hanford Site and the reference repository location are in the Pasco Basin.
Passive institutional control	(1) Permanent markers placed at a disposal site, (2) public records and archives, (3) government ownership and regulations regarding land and resource use, and (4) other methods of preserving knowledge about the location, design, and contents of a disposal system.
Perched ground water	Unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table. Perched ground water is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure.

Performance assessment	Any analysis that predicts the behavior of a system or system component under a given set of constant and/or transient conditions. Performance assessments will include estimates of the effects of uncertainties in data and modeling.
Performance measure	A set of quantitative characteristics or properties that are related to an objective and designed to measure the extent to which the objective is achieved.
Permian Basin	A region in the Central United States where, during Permian time 280 to 225 million years ago, there were many shallow seas that laid down vast beds of salt and other evaporites. The Deaf Smith site is in the Permian Basin.
Population dose	The sum of the radiation doses received by the individual members of a population exposed to a particular source or event. It is expressed in units of man-rem.
Postclosure	The period of time after the closure of the geologic repository.
Post-waste-emplacement	After the authorization of repository construction by the NRC.
Potentially acceptable site	Any site at which, after geologic studies and field mapping but before detailed geologic data gathering, the DOE undertakes preliminary drilling and geophysical testing for the definition of site location.
Potentially adverse condition	A condition that is presumed to detract from expected system performance, but further evaluation, additional data, or the identification of compensating or mitigating factors may indicate that its effect on the expected system performance is acceptable.
Preclosure	The period of time before and during the closure of the geologic repository.
Pre-waste-emplacement	Before the authorization of repository construction by the NRC.
Qualifying condition	A condition that must be satisfied for a site to be considered acceptable with respect to a specific guideline.
Quaternary Period	The second period of the Cenozoic Era, following the Tertiary, beginning 2 to 3 million years ago and extending to the present.

Radioactive waste	High-level radioactive waste and other radioactive materials, including spent nuclear fuel, that are received for emplacement in a geologic repository.
Radionuclide retardation	The process or processes that cause the time required for a given radionuclide to move between two locations to be greater than the ground-water travel time, because of physical and chemical interactions between the radionuclide and the geohydrologic unit through which the radionuclide travels.
Rem	A unit dose of ionizing radiation that has the same biological effect as 1 roentgen of x-rays; 1 rem approximately equals 1 rad for x-, gamma, or beta radiation. Thus, a rem is a unit of individual dose that allows a comparison of the effects of various radiation types as well as quantities.
Repository	Synonym for "geologic repository".
Repository closure	This term is synonymous with "closure" (10 CFR Part 960, Subpart A).
Repository construction	All excavation and mining activities associated with the construction of shafts, shaft stations, rooms, and necessary openings in the underground facility, preparatory to radioactive-waste emplacement, as well as the construction of necessary surface facilities, but excluding site-characterization activities.
Repository horizon	The horizontal plane within the host rock where the location of the repository is planned.
Repository operation	All of the functions at the site leading to and involving radioactive-waste emplacement in the underground facility, including receiving, transportation, handling, emplacement, and, if necessary, retrieval.
Repository system	The geologic setting at the site, the waste package, and the repository, all acting together to contain and isolate the waste.
Restricted area	Any area access to which is controlled by the DOE for purpose of protecting individuals from exposure to radiation and radioactive materials before repository closure, but not including any areas used as residential quarters, although a separate room or rooms in a residential building may be set apart as a restricted area.

Retrieval	The act of intentionally removing radioactive waste before repository closure from the underground location at which the waste had been previously emplaced for disposal.
Risk averse	An attitude toward an uncertain adverse impact wherein a sure loss equal to the expected value of the uncertain impact is preferred to the uncertainty.
Risk neutral	An attitude toward an uncertain adverse impact wherein the uncertainty and a sure loss equal to the expected value of the uncertainty are equally undesirable.
Risk preferring	Synonym for "risk prone."
Risk prone	An attitude toward an uncertain adverse impact wherein the uncertainty is preferred to a sure loss equal to the expected value of the uncertain impact.
Salt	The common mineral sodium chloride (NaCl) and any impurities in it.
Salt dome	A diapiric or piercement structure with a central plug that has risen through the enclosing sediments from a deep mother bed of salt.
Saturated zone	That part of the earth's crust beneath the water table in which all voids, large and small, are ideally filled with water under pressure greater than atmospheric.
Scaling factor	A numerical parameter (usually between 0 and 1) used to scale component utilities in a multiattribute utility function. The magnitudes of scaling factors represent value tradeoffs among performance measures, and not the importance of those performance measures.
Scenario	A set of postulated conditions or sequence of processes and events that could affect the performance of a repository after closure.
Sensitivity analysis	A method used to identify the inputs to an analysis or model to which the results are most sensitive.
Significant source of ground water	(1) An aquifer that: (i) is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface: (iii) has a transmissivity greater than 200 gallons per day per foot,

provided that any formation or part of a formation included within the source of ground water has a hydraulic conductivity greater than 2 gallons per day per square foot; and (iv) is capable of continuously yielding at least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of the effective date of 40 CFR Part 191, Subpart B.

Site	A potentially acceptable site or a candidate site, as appropriate, until such time as the controlled area has been established, at which time the site and the controlled area are the same.
Site characterization	Activities, whether in the laboratory or in the field, undertaken to establish the geologic conditions and the ranges of the parameters of a candidate site relevant to the location of a repository, including borings, surface excavations, excavations of exploratory shafts, limited subsurface lateral excavations and borings, and in situ testing needed to evaluate the suitability of a candidate site for the location of a repository, but not including preliminary borings and geophysical testing needed to assess whether site characterization should be undertaken.
Siting	The collection of exploration, testing, evaluation, and decision-making activities associated with the process of site screening, site nomination, site recommendation, and site approval for characterization or repository development.
Siting guidelines	Synonym for "guidelines."
Special source of ground water	Those Class I ground waters identified in accordance with the EPA's Ground-Water Protection Strategy published in August 1984 that: (1) Are within the controlled area encompassing a disposal system or are less than five kilometers beyond the controlled area; (2) are supplying drinking water for thousands of persons as of the date that the DOE chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the Act); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

Spent fuel	Synonym for "spent nuclear fuel."
Spent nuclear fuel	Fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated by reprocessing.
Surface facilities	Repository support facilities within the restricted area.
Surface water	Any waters on the surface of the Earth, including fresh and salt water, ice, and snow.
System	The geologic setting at the site, the waste package, and the repository, all acting together to contain and isolate the waste.
System performance	The complete behavior of a repository system in response to the conditions, processes, and events that may affect it.
Tectonic	Of, or pertaining to, the forces involved in, or the resulting structures or features of, "tectonics".
Tectonics	The branch of geology dealing with the broad architecture of the outer part of the Earth, that is, the regional assembling of structural or deformational features and the study of their mutual relations, origin, and historical evolution.
Tertiary	The earlier of the two geologic periods that make up the Cenozoic Era, extending from 65 million to 1.8 million years ago.
To the extent practicable	The degree to which an intended course of action is capable of being effected in a manner that is reasonable and feasible within a framework of constraints.
Tuff	A rock formed of compacted volcanic ash and dust.
Uncertainty	A situation where there are a number of possible outcomes and one does not know which of them has occurred or will occur.
Underground facility	The underground structure and the rock required for support, including mined openings and backfill materials, but excluding shafts, boreholes, and their seals.
Undisturbed performance	The predicted behavior of a disposal system, including consideration of the uncertainties in

predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

Unrestricted area	Any area that is not controlled for the protection of individuals from exposure to radiation and radioactive materials.
Unsaturated zone	The zone between the land surface and the water table. Generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure. Beneath flooded areas or in perched water bodies, the water pressure locally may be greater than atmospheric.
Utile	Unit of utility.
Utility	A quantitative measure of preference or desirability.
Utility curve	Synonym for "utility function."
Utility function	A means for converting from the unit of evaluation used for consequences or impacts to the utility scale.
Value judgments	Intrinsic human values, either personal or societal, relevant to a decision.
Value tradeoff	An expression of the relative desirability of achieving improved performance against one objective or collection of objectives versus achieving improved performance against another objective or collection of objectives. Expressing a value tradeoff requires answering the following type of question: "How much of a decrease in performance measure 1 would be tolerated to obtain an increase in performance measure 2 of one unit?"
Waste	Synonym for "radioactive waste."
Waste form	The radioactive waste materials and any encapsulating or stabilizing matrix.
Waste package	The waste form and any containers, shielding, packaging, and other sorbent materials immediately surrounding an individual waste container.
Water table	That surface in a body of ground water at which the water pressure is atmospheric.
Weight	Synonym for "scaling factor."

Appendix A

PARTICIPANTS IN THE DECISION-AIDING METHODOLOGY

Appendix A

PARTICIPANTS IN THE DECISION-AIDING METHODOLOGY

This appendix identifies the participants in the development and application of the decision-aiding methodology to the evaluation of the nominated sites for characterization; it also describes in general terms their roles in the process. About 60 people, consisting of DOE staff and management, technical specialists from support contractors, and consultants, participated in the development and application of the methodology. The process began in the summer of 1985 and was completed in April 1986.

A general flow diagram showing the process for implementing the methodology is presented in Figure A-1. The participants are listed in Tables A-1 through A-4 together with their organizational affiliations, qualifications, and the roles they played in the development and application of the methodology.

A task force was established by the Office of Geologic Repositories (OGR) in the DOE's Office of Civilian Radioactive Waste Management (OCRWM) for overseeing, coordinating, and implementing the decision-aiding methodology, and a management plan for this purpose was developed. This task force consisted of a methodology lead group, groups of technical specialists with training and experience in the specialty disciplines represented in the siting guidelines, and OGR management. In addition to DOE staff, the technical specialists included employees of the OCRWM technical support contractor (Roy F. Weston, Inc.).

The methodology lead group was composed of one DOE employee, Mr. T. P. Longo, and three consultants: Dr. P. F. Gnirk, Dr. M. W. Merkhofer, and Dr. R. L. Keeney. The three consultants were selected because of their particular expertise or type of experience. Dr. Gnirk was selected because of his previous involvement in the development of the DOE siting guidelines and many years of technical experience in geologic disposal. Drs. Merkhofer and Keeney were selected because of their experience in applications of multiattribute utility theory to similar or related problems.

The methodology lead group was responsible for developing the logical basis for the application of the methodology, for guiding all participants through the required steps of the methodology, and for eliciting from the technical staff and management the technical and value judgments required as input information. In addition, the group was responsible for compiling and editing this evaluation report. The group was under the general oversight of the senior DOE managers identified in Table A-4, and it was assisted by a number of other key professional people, named in Table A-1.

The groups of technical specialists were composed of Federal employees, technical experts from the OCRWM technical support contractor, and consultants. They are organized by discipline in Tables A-2 and A-3; the responsibilities of the various groups are consistent with functional responsibilities and staff responsibilities for program execution within the OCRWM. They were responsible for developing, with guidance from the

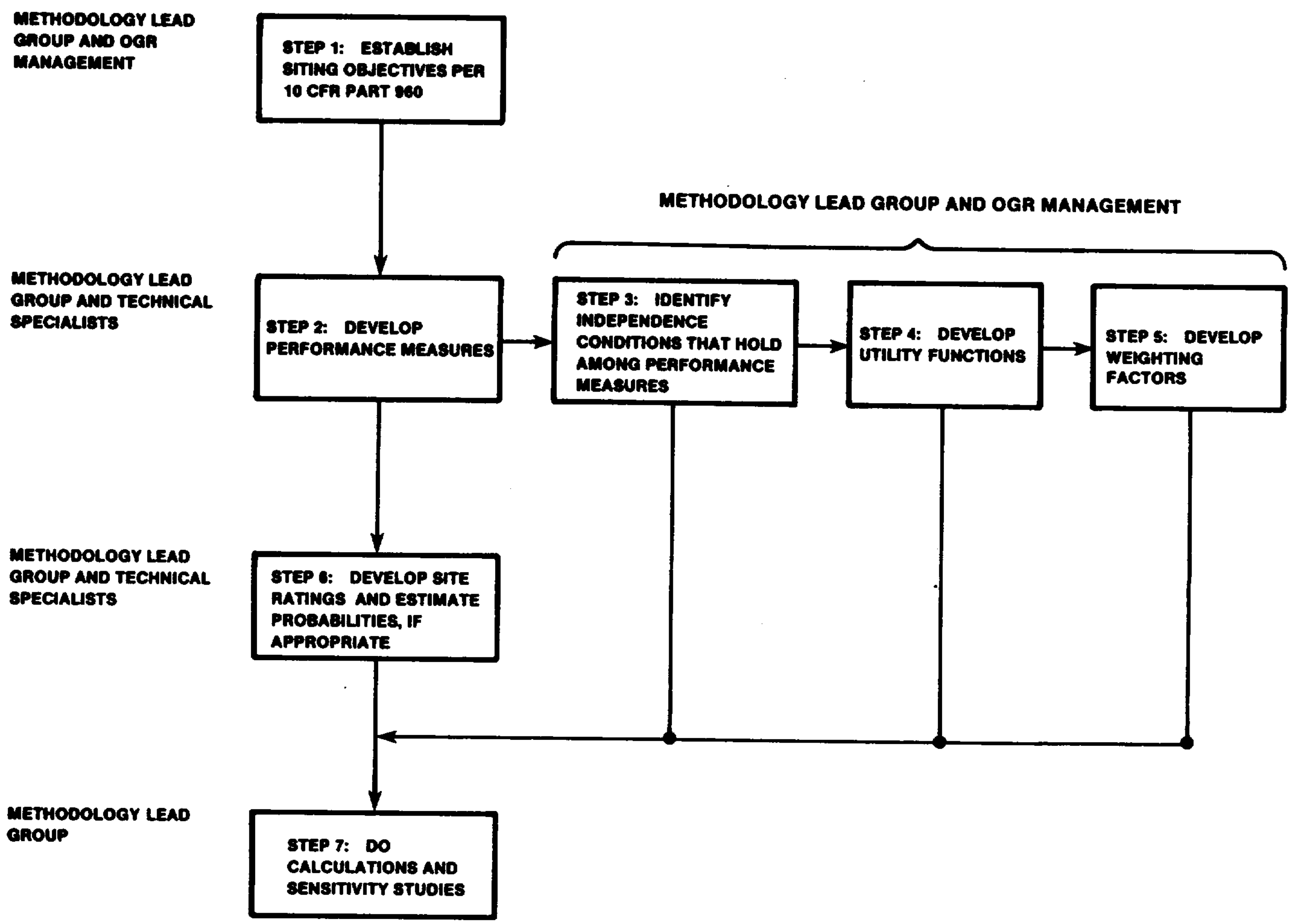

Figure A-1. General flow of activities and division of responsibilities for implementing the formal methodology.

methodology lead group, the influence diagrams and associated performance measures for the various siting objectives. They were also responsible for scoring the sites against the performance measures. An ad hoc technical advisory group, composed of technical specialists who were not directly involved with the development and implementation of the methodology, provided advice to the postclosure technical specialists on the development of the performance measures. Also listed in Table A-2, the members of this advisory group were selected because of their expertise in performance assessment.

Several OGR managers, listed in Table A-4, participated in those parts of the methodology that require value or policy judgments. These included, in particular, the specification of siting objectives, the verification of independence assumptions, and the specification of utility curves and weighting factors. In addition, the OGR managers reviewed the progress of the implementation of the methodology on a regular basis.

Table A-1. Participants in the development and application of the methodology

Name	Affiliation	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Decision analysis	Other areas	Role[A]
			METHODOLOGY LEAD GROUP				
T. P. Longo	DOE/OGR[B]	M.S. in geochemistry, University of Maryland (1979)	Repository siting, geosciences, DOE repository program	6		1	Lead; all steps
P. F. Gnirk	RE/SPEC Inc.	Ph.D. in rock mechanics, University of Minnesota (1966)	Rock mechanics, repository engineering, DOE siting guidelines	15		10	All steps
R. L. Keeney[C]	University of Southern California	Ph.D. in operations research, Massachusetts Institute of Technology (1969)	Decision analysis, risk analysis, siting energy facilities		15	5	All steps
M. W. Merkhofer	Applied Decision Analysis, Inc.	Ph.D. in engineering economic systems, Stanford University (1975)	Decision analysis, risk assessment, environmental analysis		14	3	All steps
			KEY PERSONNEL SUPPORTING THE METHODOLOGY LEAD GROUP				
D. M. Murphy[C]	Applied Decision Analysis, Inc.	M.S. in engineering economic systems, Stanford University (1985)	Decision analysis		1	1	2, 6
E. Olmstead[D]	Independent	M.S. in engineering economic systems, Stanford University (1982)	Decision analysis		2	2	2
L. G. Shaw	Weston	Ph.D. in political science, West Virginia University (1982)	Institutional affairs and socioeconomic analysis	3		15	1, 2, 6
D. L. Siefken	Weston	M.S. in geology, University of Florida (1974)	Geohydrology, geotechnical engineering, 10 CFR Part 60	7		5	1, 2, 6

Table A-1. Participants in the development and application of the methodology (continued)

Name	Affiliation	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Decision analysis	Years of professional experience: Other areas	Role[A]
KEY PERSONNEL SUPPORTING THE METHODOLOGY LEAD GROUP (continued)							
A. Sicherman	Lawrence Livermore National Laboratory	M.S. in operations research, Massachusetts Institute of Technology (1975)	Decision analysis, computer modeling		11	5	7
R. G. Schwartz	Applied Decision Analysis, Inc.	Ph.D. in engineering economic systems, Stanford University (1985)	Decision analysis		2	2	7

[A] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

[B] Office of Geologic Repositories.

[C] Started January 17, 1986.

[D] Until January 1, 1986.

Table A-2. Postclosure technical specialists and their roles in the development and application of the methodology

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			POSTCLOSURE TECHNICAL SPECIALISTS			
A. J. Jelacic	DOE/OGR	Ph.D. in geology, University of Rochester (1971)	Planning and management, geology	2	13	Lead; 1, 2, 6
J. E. Rhoderick	DOE/OGR	B.S. in geology, James Madison University (1977)	Engineering geology, licensing	7	1	2, 6
G. L. Faulkner	USGS--DOE/OGR	M.A. in geology, University of Wyoming (1950)	Hydrology, hydrogeology, petroleum geology	2	34	2, 6
K. S. Czyscinski	Weston	Ph.D. in geochemistry, University of South Carolina (1975)	Ground-water chemistry, waste-package performance assessment	7	4	2, 6
W. M. Hewitt	Weston	M.S. in nuclear engineering, Catholic University of America (1980)	Safety assessments, human interference, 10 CFR Part 60, DOE siting guidelines	10	8	2, 6
R. E. Jackson	Weston	Ph.D. in geology, University of North Carolina (1973)	Geotechnology, seismology, licensing	5	11	2, 6
J. K. Kimball	Weston	M.S. in geology (seismology), University of Michigan (1980)	Seismology, geophysical investigations, licensing	2	4	2, 6
S. V. Panno	Weston	M.S. in geology, Southern Illinois University (1978)	Ground-water chemistry, corrosion	5	5	2, 6
M. W. Pendleton	Weston	M.S. in geology, Rutgers University (1973)	Geology, hydrology, 10 CFR Part 60	5	8	2, 6

Table A-2. Postclosure technical specialists and their roles in development and application of the methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			POSTCLOSURE TECHNICAL SPECIALISTS (continued)			
L. D. Rickertsen	Weston	Ph.D. in nuclear physics, Yale University (1972)	Repository performance assessment, numerical modeling	10	3	2, 6
D. L. Siefken	Weston	M.S. in geology, University of Florida (1974)	Geohydrology, geotechnical engineering, 10 CFR Part 60	7	5	1, 2, 6
			AD HOC TECHNICAL ADVISORY GROUP			
F. W. Bingham	Sandia National Laboratories	Ph.D. in nuclear physics, Indiana University (1962)	Performance assessment (salt, tuff)	10	14	1, 2
J. E. Campbell	Intera Technologies, Inc.	Ph.D. in physics, Virginia Polytechnic Institute (1969)	Performance assessment (salt)	10	7	1, 2
B. Sagar	Rockwell-Hanford Operations	Ph.D. in hydrology, University of Arizona (1973)	Performance assessment (basalt), numerical modeling, fluid mechanics	5	17	1, 2
W. D. Weart	Sandia National Laboratories	Ph.D. in geophysics, University of Wisconsin (1961)	Performance assessment (salt)	12	18	1, 2

[A] Acronyms: OGR, Office of Geologic Repositories; USGS, U.S. Geological Survey.
[B] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

Table A-3. Preclosure technical specialists and their roles in development and application of the methodology

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			PRECLOSURE RADIOLOGICAL SAFETY			
R. S. Pelletier	DOE/ESH	B.S. in civil engineering, Merrimack College (1971)	Environmental protection, defense-waste management and disposal	5	10	Lead; 2, 6
V. W. Lowery	DOE/OGR	M.S. in physics, University of Akron (1968)	Nuclear engineering, repository design	3	14	2, 6
W. M. Hewitt	Weston	M.S. in nuclear engineering, Catholic University of America (1980)	Safety assessments, 10 CFR Part 60, DOE siting guidelines	10	8	2, 6
W. C. McClain	Weston	Ph.D. in mining engineering, University of Newcastle-Upon-Tyne (1963)	Repository engineering, rock mechanics, disposal and repository siting technology	22	0	2
G. Martin, Jr.	Weston	M.S. in nuclear engineering, Polytechnic Institute of New York (1976)	Radiological engineering, health physics	1	12	2, 6
L. G. Shaw	Weston	Ph.D. in political science, West Virginia University (1980)	Institutional affairs, socioeconomic analysis	3	15	2, 6
D. A. Waite	Battelle-ONWI	Ph.D. in general engineering, Oklahoma State University (1972)	Health physics, radiological assessment, waste management	8	12	2
			ENVIRONMENTAL QUALITY			
G. J. Parker	DOE/OGR	M.S. in engineering management, Catholic University of America (1982)	Environmental, regulatory, and siting activities	2	18	Lead; 1, 2, 6
R. K. Sharma	DOE/OGR	Ph.D. in ecology, Utah State University (1968)	Environmental assessments, regulatory compliance	2	23	2, 6
D. M. Valentine	DOE/OGR	J.D., Howard University (1975)	Legislation, commercial law, environmental specialty	0.5	9	6

Table A-3. Preclosure technical specialists and their roles in development and application of the methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			ENVIRONMENTAL QUALITY (continued)			
C. E. Bradley	DOE/ESH	M.S. in regional planning, University of Pennsylvania (1975)	Environmental assessments, regulatory compliance	3	15	1, 2, 6
J. L. Friedman	Weston	Ph.D. in anthropology, Washington State University (1975)	Cultural resource management, environmental issues, archaeological issues	1	12	2, 6
D. E. Keough	Weston	B.S. in environmental resource management, Pennsylvania State University (1978)	Applied ecology, remedial environmental actions	3	4	2
B. L. Nichols	Science Applications, Inc.	B.S. in natural resources, University of Wisconsin (1964)	Environmental impact assessments, regulatory compliance, aquatic ecology	5	17	2
K. A. St. John	Weston	M.S. in environmental management, Duke University (1980)	Environmental impact assessments, environmental regulations	4	4	2, 6
R. L. Toft	Weston	M.S. in environmental management, Duke University (1977)	Environmental impact assessments, environmental regulations	3	7	2, 6
A. H. Vogel	Weston	B.S. in geology, Dickinson College (1983)	Environmental management, hazardous waste	0	3	6
			SOCIOECONOMICS			
B. G. Gale	DOE/OGR	Ph.D. in history and philosophy of science, University of Chicago (1970)	Socioeconomics, intergovernmental analysis, financial assistance programming	3	12	Lead; 1, 2, 6

Table A-3. Preclosure technical specialists and their roles in development and application of the methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
			SOCIOECONOMICS (continued)			
A. M. McDonough	DOE/OGR	B.S. in economics, University of Pennsylvania (1974)	Natural resource analysis, transportation, program management, economics	1	10	2, 6
C. G. Halloran	Weston	B.A. in history and public policy, Duke University (1983)	Socioeconomics, institutional analysis	3	-	2, 6
L. G. Shaw	Weston	Ph.D. in political science, West Virginia University (1982)	Institutional affairs, socioeconomic analysis	3	15	1, 2, 6
R. K. Travis	Weston	M.A. in economic geography, University of Pittsburgh (1974)	Socioeconomics	1	11	2, 6
			TRANSPORTATION			
E. L. Wilmot	DOE/OSTS	M.S. in ceramic engineering, nuclear materials, University of Washington (1972)	Transportation risk analysis, radiological protection, cask design	10	4	Lead; 1, 2, 6
L. S. Marks	DOE/OSTS	B.A. in chemistry, Queens College of City University of New York (1970)	Transportation risk analysis, statistical analysis	1	14	2, 6
P. A. Bolton	Weston	M.S. in biochemistry and microbiology, University of Connecticut (1960)	Radioactive-waste transportation, emergency response	3	15	2, 6
			EASE AND COST OF SITING, CONSTRUCTION, OPERATION, AND CLOSURE			
M. W. Frei	DOE/OGR	M.S. in nuclear engineering, University of Washington (1976)	Repository design and development, nuclear engineering	8	3	Lead; 2, 6

Table A-3. Preclosure technical specialists and their roles in development and application of methodology (continued)

Name	Affiliation[A]	Academic training	Areas of expertise and experience	Years of professional experience: Geologic disposal	Years of professional experience: Other areas	Role[B]
		EASE AND COST OF SITING, CONSTRUCTION, OPERATION, AND CLOSURE (continued)				
J. J. Fiore	DOE/OGR	M.S. in business administration, University of Maryland (1978)	Repository cost analysis, mechanical engineering	6	7	2, 6
S. P. Schneider	DOE/OGR	B.S. in chemical engineering, University of Maryland (1978)	Repository cost and design analysis, spent-fuel storage technology	6	2	2, 6
P. L. Collyer	ICF	M.S. in economic geology, Syracuse University (1971)	Mine engineering and design, mine safety	5	11	2
D. A. Gardner	Weston	M.S. in nuclear engineering, State University of New York (1970)	Repository design and cost analysis	2	16	2, 6
J. W. Nelson[C]	Weston	M.S. in civil engineering (geotechnical), Massachusetts Institute of Technology (1977)	Repository design engineering, rock mechanics	6	3	2, 6
G. W. Toth	Weston	B.S. in industrial engineering, Pennsylvania State University (1967)	Repository cost analysis, underground repository cost modeling	1	18	2

[A] Acronyms: ESH, Environment, Safety and Health; OGR, Office of Geologic Repositories; ONWI, Office of Nuclear Waste Isolation; OSTS, Office of Storage and Transportation Systems.

[B] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

[C] Until January 31, 1986.

Table A-4. DOE/OCRWM Management and their roles in the development and application of the methodology

Name	Position and affiliation	Academic training	Areas of expertise and experience	Years of professional experience: DOE/OCRWM[A]	Years of professional experience: Other Federal agencies	Years of professional experience: Private industry	Role[B]
W. J. Purcell	Associate Director for the Office of Geologic Repositories, DOE/OCRWM	M.S. in mechanical engineering, Carnegie Mellon University (1949)	Project management, management of research and development, engineering design, nuclear engineering	1.5	3	38	1,3,4,5
T. H. Isaacs	Deputy Associate Director for the Office of Geologic Repositories, DOE/OCRWM	M.S. in engineering and applied physics, Harvard University (1971)	Waste-management policy, program management, nuclear engineering, fuel-cycle activities	2	16	1	1,3,4,5
E. S. Burton	Director, Siting Division, Office of Geologic Repositories, DOE/OCRWM	B.A. in mathematics, Amherst College (1951)	Waste management, environmental policy analysis, program management, facility siting, statistics	4	12	14	1,3,4,5
R. Stein	Director, Engineering and Geotechnology Division, Office of Geologic Repositories, DOE/OCRWM	B.S. in chemical engineering, University of Pittsburgh (1954)	Waste management, project management, nuclear engineering, repository engineering, siting and licensing	8	17	7	1,3,4,5

[A] Includes the DOE Office of Civilian Radioactive Waste Management and predecessor agencies that were responsible for the geologic disposal program before the Nuclear Waste Policy Act of 1982.

[B] The numbers in this column correspond to the steps in the methodology (Figure A-1) as follows: (1) establish siting objectives; (2) develop influence diagrams and performance measures; (3) identify independence conditions that hold among the performance measures; (4) develop utility functions; (5) develop weighting factors; (6) develop site ratings and estimate probabilities, if appropriate; and (7) perform calculations and sensitivity studies.

Appendix B

INFLUENCE DIAGRAM AND PERFORMANCE MEASURES FOR THE POSTCLOSURE OBJECTIVES

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Appendix B

INFLUENCE DIAGRAM AND PERFORMANCE MEASURES FOR THE POSTCLOSURE OBJECTIVES

B.1 INTRODUCTION

Chapter 3 briefly summarizes the influence diagram and performance measures for evaluating the long-term waste-isolation capabilities of the five nominated sites. This appendix provides additional detail on the influence diagram and the development of the performance measures. In addition, it illustrates the application of the performance-measure scales in three examples.

The overall objective for the postclosure period is to minimize adverse impacts on the health and safety of the public (see Figure B-1). Specifically, the objective is to minimize the number of radiological health effects experienced by the public and attributable to the repository. Directly related to this objective are the DOE siting guidelines of 10 CFR Part 960, Subpart C (DOE, 1984). For example, the postclosure system guideline specifies waste containment and isolation requirements based on the regulatory standards established by the Nuclear Regulatory Commission (NRC) and the Environmental Protection Agency (EPA) for the protection of the health and safety of the public in 10 CFR Part 60 and 40 CFR Part 191, respectively (NRC, 1983; EPA, 1985a). Each of the eight postclosure technical guidelines is related to the containment and isolation of the wastes for 10,000 years. In addition, the first three technical guidelines include conditions for the geohydrology, geochemistry, and rock characteristics of a site--that is, the natural barriers--that relate to the performance of a repository for up to 100,000 years.

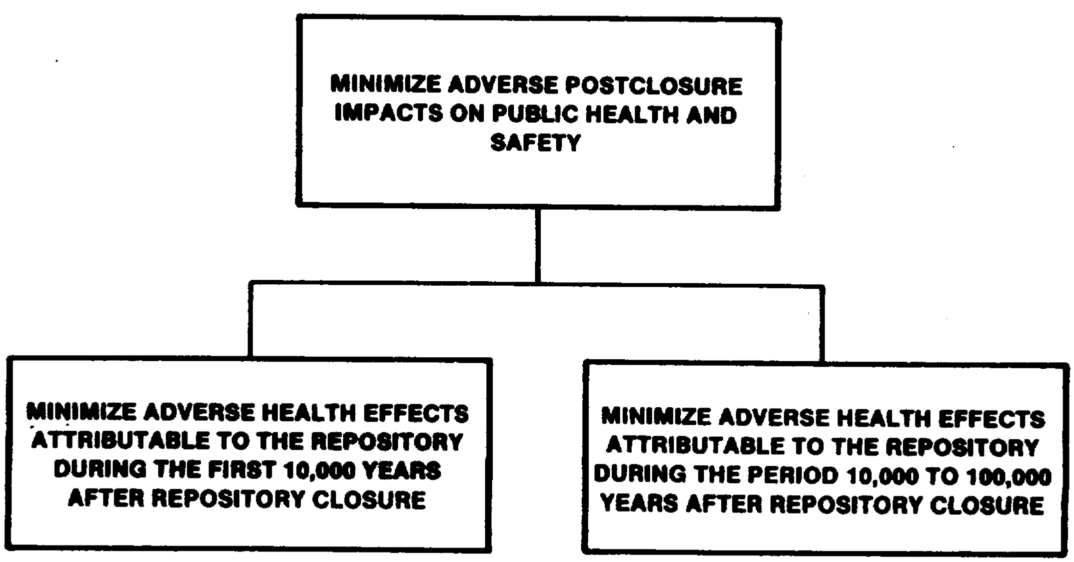

Figure B-1. Postclosure objectives hierarchy.

The overall postclosure objective is divided into two subobjectives that are defined as follows:

- Minimize the adverse health effects attributable to the repository during the first 10,000 years after closure.
- Minimize the adverse health effects attributable to the repository during the period 10,000 to 100,000 years after closure.

These two time periods allow independent judgments in two distinct time intervals that are considered in the postclosure guidelines of 10 CFR Part 960, Subpart C.

B.2 INFLUENCE DIAGRAM

To aid in the development of the postclosure performance measures, a detailed influence diagram was constructed (Figure B-2). This graphic device illustrates the influence of important site characteristics on the ability of a repository to meet the waste containment and isolation requirements specified in 10 CFR Part 60 and 40 CFR Part 191, Subpart B. The site characteristics have been numbered to facilitate their description in the text that follows. The characteristics that are believed to be the most important are shown as double ellipses.

The most important factors that affect the number of postclosure health effects are the number of people exposed (the population at risk (2)) and the radiation dose each person receives (3). Radiation doses are assumed to depend on radionuclide releases to the accessible environment and the transport, retardation, dispersion, accumulation, and uptake of the released radionuclides along a variety of environmental pathways. These pathways determine the doses received by people from ingestion, inhalation, or immersion and are the factors designated 19, 21, 22, 23, etc., in Figure B-2.

Although the ingestion, inhalation, and immersion dose pathways in the accessible environment are shown on the influence diagram for completeness, evaluations of the factors influencing the accessible environment over the next 10,000 to 100,000 years are impractical, and, because the estimated radionuclide releases are so small, a comparison of the sites against these factors was deemed unnecessary. The preliminary performance assessments reported in the environmental assessments (DOE, 1986a-e) show that the releases to the accessible environment over the next 10,000 to 100,000 years should be relatively insignificant. Indeed, the estimated ground-water-travel times indicate that the radionuclides released from the engineered-barrier system are not expected to reach the ground surface or discharge into surface-water bodies during this time period. Likely pathways to the biosphere would, therefore, consist of wells or borings drilled for water or for mineral exploration. For both of these pathways, releases within the controlled area have been evaluated in the postclosure analysis described here and in Chapter 3. The DOE therefore adopted an approach to site evaluations that is based on comparing the cumulative radionuclide releases to the accessible environment (23) against the EPA release limits--an approach

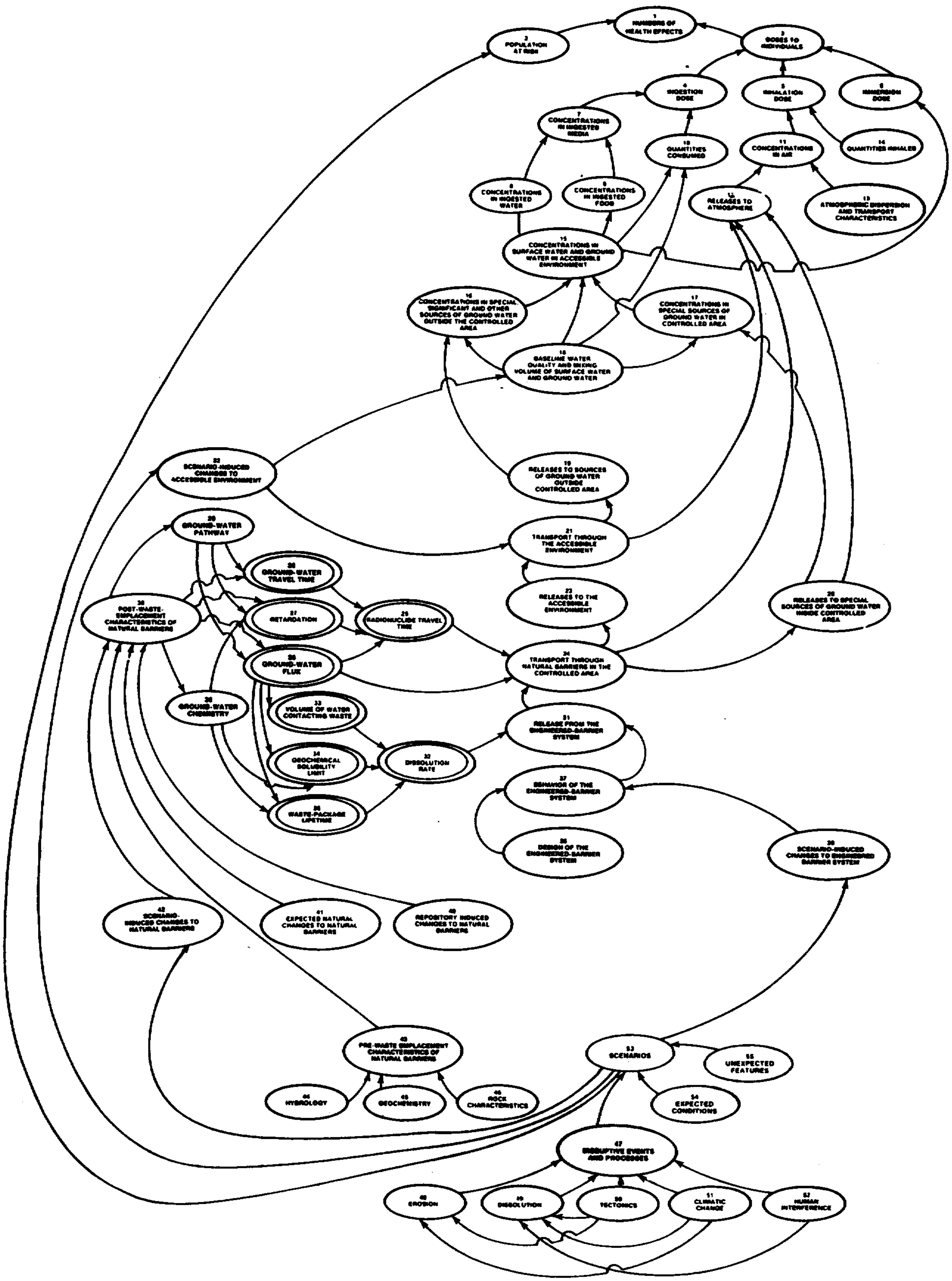

Figure B-2. Relationships among the factors influencing the numbers of postclosure health effects attributable to the repository.

that is consistent with the EPA and the NRC regulations. Accordingly, the DOE has not evaluated differences among the sites with respect to pathways to the biosphere within the accessible environment.

Factors 23, 24, 31, 37 and 38 in Figure B-2 represent a simplified illustration of the defense in depth provided by the multiple barriers of a geologic repository against releases of radionuclides to the accessible environment. The influence diagram shows that the releases to the accessible environment in the postclosure period (23) are largely determined, in the expected case, by the releases from the engineered-barrier system (31) and the transport of the radionuclides though the natural barriers in the controlled area (24). In some instances, there may be scenario-induced changes to the engineered-barrier system (39) or the natural-barrier system (42), and these changes would affect releases to the accessible environment.

The types and quantities of radionuclides transported and the period of time over which transport occurs depend chiefly on the radionuclide-travel time (25), the ground-water flux (28), and the geochemical conditions of the geohydrologic units in which transport occurs (27, 34, 36). The radionuclide-travel time may depend on the ground-water-travel time (26) if ground water is the principal transporting medium and on the processes that retard the movement of the dissolved radionuclides in relation to the movement of the ground water (27). Each of these factors is determined by the type and characteristics of the ground-water pathway (29) and the postclosure characteristics of the natural barriers (30) (e.g., hydraulic gradients, conductivity, effective porosity, and geochemistry).

The radionuclides transported through the natural barriers originate as releases from the engineered-barrier system (31). The types and quantities of radionuclides released from the engineered-barrier system are related to the behavior of the engineered-barrier system (37) and the rate of release for individual radionuclides (32). The behavior of the engineered-barrier system (e.g., the response to the thermal pulse introduced by the emplaced waste) is related to the design of the engineered-barrier system (38), such as waste-package spacing, and any changes in the engineered-barrier system that are induced by disruptive processes and events (39), such as the breach of waste packages by fault displacement.

The rate of release of a particular radionuclide from the engineered-barrier system depends on the volume of ground water in contact with the waste (33), the concentration of that radionuclide in that water (34), and the waste-package lifetime (35). The volume of ground water in contact with the waste is influenced by the ground-water flux, while the concentration of radionuclides and the waste-package lifetime are related to the ground-water temperature and chemistry, which, in turn, are influenced by the post-waste-emplacement characteristics of the natural barriers.

The post-waste-emplacement characteristics of the natural barriers are affected by the changes expected to occur in the natural barriers because of ongoing or expected geologic processes (e.g., the erosion of the land surface), repository-induced changes in the natural barriers (e.g., thermally induced uplift), pre-waste-emplacement characteristics (e.g., hydraulic gradients), and changes in the characteristics of the natural barriers induced by disruptive processes and events (factors 40, 41, 42, and 43).

The ability of a site to isolate waste from the accessible environment for thousands of years after repository closure is influenced by processes, events, and conditions that are both expected and unexpected. A postulated set of conditions and processes, or sequence of events, at a site is known as a scenario (53). For the purpose of comparing the nominated sites, three kinds of scenarios were developed: (1) a scenario for conditions, processes, and events that are expected at a site because of existing information (factor 54); (2) a scenario for unexpected features that may affect repository performance, including such things as undetected geologic structures and anomalies and unforeseen responses of the rock mass to the emplacement of heat-generating wastes (factor 55); and (3) scenarios that lead to the disruption of the expected repository behavior through natural processes and events or human interference (factor 47). It is intended that the scenarios reflect the favorable and potentially adverse conditions (10 CFR Part 960, Subpart C) identified at the sites in the final environmental assessments (DOE, 1986a-e).

The changes in the characteristics of the natural barriers that are induced by disruptive processes and events occurring any time during the first 10,000 years after closure are evaluated (as they affect releases from the engineered-barrier system or transport through natural barriers in the controlled area) for both the first 10,000 years and for the period 10,000 to 100,000 years after repository closure. Disruptive processes and events include tectonic activity (50), erosion (48), dissolution (49), and human interference (52). The rates of erosion or dissolution at a site may be affected by other processes, such as tectonic activity, climatic changes (51), or human interference.

Although some of the disruptive events may affect the size of the population at risk, this is not a discriminator among the sites because of the inability to project future population densities and distributions over the next 10,000 years. Accordingly, the relationship is shown on the influence diagram but was not used in the evaluation of sites.

B.3 PERFORMANCE MEASURES

B.3.1 BACKGROUND INFORMATION

The overall objective for the postclosure performance of a repository is to minimize adverse impacts on the health and safety of the public. As shown in Figure B-1, this objective is divided into two lower-level objectives that are stated in terms of minimizing adverse health effects in the public during two specific time periods after repository closure: during the first 10,000 years and from 10,000 to 100,000 years. Health effects were used in the risk assessment conducted by the EPA to establish the environmental standards for geologic disposal under 40 CFR Part 191, Subpart B. The health effects of concern are the cancer deaths that could result from exposure to the radionuclides released from the repository to the accessible environment. Genetic effects that could result from exposure to these radionuclides were also considered by the EPA, but the results of detailed evaluations led to the conclusion that genetic effects are not likely to be significant in comparison with somatic effects.

The primary-containment requirements of the EPA standards for the postclosure system, as embodied principally in Table 1 of Appendix A of 40 CFR Part 191, specify the allowable cumulative releases of radionuclides to the accessible environment per 1000 metric tons of uranium (MTHM) for the first 10,000 years after repository closure. These release limits were developed by the EPA after evaluations of the expected performance of geologic repositories in generic basalt, granite, salt, and tuff formations, assuming (1) very general models of environmental transport; (2) a linear, nonthreshold dose-effect relationship between radiation exposure and premature deaths from cancer; and, (3) current population distributions and death rates. For each 1000 MTHM, the allowable cumulative release limits specified by the EPA represent the potential for approximately 10 cancer deaths in 10,000 years. Because of the assumption of a linear dose-effect relationship between radiation exposure and deaths from cancer, releases are in effect proportional to health effects, and the former can be taken as a useful surrogate for the latter.

The EPA specifies in 40 CFR Part 191, Subpart B, that, for the first 10,000 years after closure, the releases to the accessible environment must not exceed the limits given in Table 1 of Appendix A of that regulation. The EPA chose this time period partly because compliance with quantitative standards for a substantially longer period would entail projections of releases that reflect considerably more uncertainty. Furthermore, it was felt that a repository system capable of meeting the containment requirements for 10,000 years would continue to protect people and the environment well beyond 10,000 years. On the other hand, the DOE siting guidelines (10 CFR 960.3-1-5) require the sites being considered for development as a repository to be compared in terms of the projected releases from an undisturbed repository over 100,000 years. The DOE therefore chose to evaluate site performance under expected conditions for two time periods: for scenarios involving unexpected features and disruptive processes and events during the first 10,000 years and during the period 10,000 to 100,000 years after closure. However, evaluations of repository performance were carried out for both time periods only if the scenario was judged likely to occur during the first 10,000 years (i.e., with a probability greater than 1 chance in 10,000); that is, the consequences of such scenarios were not evaluated if they were postulated to occur after the first 10,000 years. The effect of relaxing this assumption on the postclosure analysis was examined in a sensitivity analysis (see Figure 3-14).

Additional postclosure objectives and associated performance measures were considered. For example, objectives could have been developed in terms of the individual protection requirements (40 CFR 191.15) and the ground-water protection requirements (40 CFR 191.16) of the EPA standards because of their relationship to health effects. However, it was not practical to do so because the bounding analyses presented in Section 6.4.2 of the environmental assessments (EAs) for the nominated sites (DOE, 1986a-e) provide no basis for discrimination among sites. That is, these analyses indicate no impacts on individuals or ground water during the first 1000 years at any of the sites for undisturbed performance of the repository because no releases to special or significant sources of water are expected. Because of the inability to discriminate among sites on this basis, objectives related to special or significant sources of ground water were not included in the objectives hierarchy. Similarly, postclosure performance measures were not developed in terms of the characteristics of the accessible environment, such as future human populations or environmental pathways, because predictions of such conditions for 10,000 years are not reliable.

B.3.2 PERFORMANCE-MEASURE SCALES

The performance measures are defined in terms of radionuclide releases as follows:

- The cumulative release of radionuclides to the accessible environment during the first 10,000 years after repository closure.
- The cumulative release of radionuclides to the accessible environment during the period 10,000 to 100,000 years after repository closure.

The scale of each of these performance measures is defined in terms of the release limits specified as the containment requirements by Table 1 of Appendix A of 40 CFR Part 191. These requirements specify the allowable cumulative releases of individual radionuclides to the accessible environment for the first 10,000 years after repository closure in terms of curies per 1000 MTHM. These requirements also specify the way in which these individual release limits are to be combined to define an overall system release limit. The scales for the performance measures are expressed in terms of this release limit, as shown in Figures B-3 and B-4. The scale for the first performance measure is chosen to range between 0 and 10, where a score of 10 corresponds to a cumulative release of 0.0001 of the release limit and a score of 0 corresponds to 10 times the release limit. The evaluations in Section 6.4.2 of the EAs suggested that the expected releases to the accessible environment at all nominated sites may be so low that a linear scale in terms of releases may not provide sufficient discrimination among the sites. Therefore, a logarithmic scale in terms of multiples of the EPA release limits was chosen; that is, a score of 0 corresponds to 10 times the EPA release limits, a score of 2 corresponds to the EPA release limits, a score of 4 corresponds to 0.1 of the limits, and so forth.

The scale for the second measure (10,000 years to 100,000 years) is analogous to the scale for the first measure except that now a score of 0 corresponds to 100 times the EPA release limits for the first 10,000 years, a score of 2 corresponds to 10 times the limits, and so forth. Therefore, the scale increments in releases for this 90,000-year period are 10 times those for the first 10,000 years.

Also shown on the right of Figures B-3 and B-4 are the site characteristics for which the radionuclide releases specified on the left are judged to be reasonably equivalent. As shown in the influence diagram of Figure B-2, the site characteristics important to the determination of releases include the ground-water-travel time, the ground-water flux, the solubility of key radionuclides, and retardation factors for key radionuclides. There are many combinations of such characteristics that could lead to an equivalent release or score. For example, the release from a site with a long ground-water-travel time may be the same as that from a site with a very low solubility of key radionuclides. These sites, in turn, may be equivalent to another site that has both a moderate ground-water-travel time and a moderate retardation of radionuclide movement in relation to the ground-water velocity.

It is possible to aggregate these site characteristics in terms of the way they affect releases from the engineered-barrier system and transport through the natural barriers by means of two performance factors:

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the First 10,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.0001	10 9	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are insignificant. This judgment is based on a combination of site characteristics that implies an extremely limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 1 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that very strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 200,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.001	8 7	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are extremely small. This judgment is based on a combination of site characteristics that implies a very limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 3 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 150,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.01	6 5	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are very small. This judgment is based on a combination of site characteristics that implies a limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 10 percent of the EPA release limits because of a very low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 100,000 years because of very favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a very long ground-water travel time.
0.1	4 3	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 30 percent of the EPA release limits because of a low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 50,000 years because of favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a long ground-water travel time.
1	2 1	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies high potential for releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 100 percent of the EPA release limits because of a high volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that weakly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is less than 10,000 years because of moderate retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a moderate ground-water travel time.
10	0	The characteristics and conditions at the site are such that, during the first 10,000 years after closure, radionuclide releases to the accessible environment are extremely significant. This judgment is based on a combination of site characteristics that implies an extremely high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 10,000 years is about 1000 percent of the EPA release limits because of an extremely high volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that enhance waste dissolution. • The median travel time to the accessible environment of any key radionuclide is less than 3000 years because of little retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a short ground-water travel time.

NOTE: It must be kept in mind that the set of site characteristics that leads to any given score is not unique. Equivalent combinations of performance factors are given in Table B-1.

Figure B-3. Scale used to aid the judgmental estimation of releases during the first 10,000 years after repository closure.

PERFORMANCE MEASURE—Cumulative Releases of Radionuclides to the Accessible Environment During the Time Period 10,000 to 100,000 Years After Repository Closure

Cumulative Releases Over the First 10,000 Years as Multiples of the EPA Release Limits	Scale	Characteristics of the Site for Which the Cumulative Releases on the Left Are Judged To Be Reasonable
0.001	10 9	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are insignificant. This judgment is based on a combination of site characteristics that implies an extremely limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground-water in 90,000 years is about 10 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that very strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 300,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.01	8 7	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are extremely small. This judgment is based on a combination of site characteristics that implies a very limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 30 percent of the EPA release limits because of an extremely low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that strongly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 250,000 years because of extremely favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with an extremely long ground-water travel time.
0.1	6 5	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are very small. This judgment is based on a combination of site characteristics that implies a limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 100 percent of the EPA release limits because of a very low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 200,000 years because of very favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a very long ground-water travel time.
1	4 3	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are small. This judgment is based on a combination of site characteristics that implies some limited potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 300 percent of the EPA release limits because of a low volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 150,000 years because of favorable retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a long ground-water travel time.
10	2 1	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are significant. This judgment is based on a combination of site characteristics that implies a high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 1000 percent of the EPA release limits because of a high volumetric flow rate of ground water across or through the host rock together with geochemical ground water conditions that weakly inhibit waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 100,000 years because of moderate retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a moderate ground-water travel time.
100	0	The characteristics and conditions at the site are such that, during the period 10,000 to 100,000 years after closure, radionuclide releases to the accessible environment are extremely significant. This judgment is based on a combination of site characteristics that implies an extremely high potential for radionuclide releases from the engineered-barrier system and transport through the natural barriers to the accessible environment. One such combination would be— • The quantity of radionuclides potentially dissolved in ground water in 90,000 years is about 10,000 percent of the EPA release limits because of an extremely high volumetric flow rate of ground water across or through the host rock together with geochemical ground-water conditions that enhance waste dissolution. • The median travel time to the accessible environment of any key radionuclide is about 10,000 years because of little retardation of any reactive or nonreactive radionuclides by physical and chemical processes during transport together with a short ground-water travel time.

NOTE: It must be kept in mind that the set of site characteristics that leads to any given score is not unique. Equivalent combinations of performance factors are given in Table B-2.

Figure B-4. Scale used to aid the judgmental estimation of releases occurring during the period 10,000 to 100,000 years after repository closure.

- A factor for release from the engineered-barrier system, F, which is a measure of the amount of radionuclides that can be expected to be dissolved into the ground water during the period of interest.

- A factor for transport through the natural barriers, T_i, which is a measure of the travel time of key radionuclides through the natural barriers to the accessible environment under post-waste-emplacement conditions.

The first performance factor, F, would be given by the sum of the ratios of the cumulative releases to the accessible environment to the EPA release limits if these cumulative releases were predicted in a performance analysis. For direct-release scenarios, F could be estimated by considering the quantity of the total radionuclide inventory that is released in terms of the EPA release limits. For indirect-release scenarios, in which the radionuclides are dissolved into ground water that moves to the accessible environment, F can be estimated from a simple relationship that depends on the ability of the ground water to dissolve the waste. In this case, F is approximated by the sum of the ratios of the maximum quantities of radionuclides dissolved during the period of interest to the quantities allowable under the EPA release limits:

$$F = \sum_{i} QC_i/RL_i,$$

where

Q = total volume of ground water (cubic meters per 1000 MTHM) that will be in contact with the waste during the period of interest

C_i = the maximum concentration of each radionuclide (curies per cubic meter of ground water) based on solubility, inventory, or other factors

RL_i = the release limit for each radionuclide (curies per 1000 MTHM) as specified in Table 1 of Appendix A of 40 CFR Part 191

In general, the performance factor F depends on two site characteristics:

1. Ground-water flow through or across the host rock.

2. The chemical conditions of the ground water insofar as they may relate to its capability to dissolve radionuclides.

As an example of the dependence of F on the ground-water flow through the host rock, the following can be considered: for a host rock characterized by a constant, uniform ground-water flux, the term Q can be estimated from

$$Q = fAt,$$

where

f = ground-water flux (cubic meters per square meter per year)

A = effective cross-sectional area (square meters per 1000 MTHM) through which the ground water flows

t = period of interest (years)

It is the total volume of ground water available for the dissolution of waste that is of interest here. The volume of water that is in contact with the waste also depends on the pathways to and around the waste package. With regard to the dependence of F on the site geochemistry, C_i can be estimated from the isotopic solubilities, S_i, of the radionuclides and waste-form constituents in the ground water at a site, taking into account the expected repository conditions (e.g., temperature and controlling phases).

The second performance factor, T_i, is the travel time of the i^{th} key radionuclide from the engineered-barrier system to the accessible environment under post-waste-emplacement conditions. A key radionuclide is defined as one that contributes significantly to the quantity of radionuclides that could be dissolved in the ground water during the period of interest (e.g., more than 1 percent of the quantity F above). An example of the way T_i can be estimated is given by the expression

$$T_i = R_i T,$$

where R_i is the retardation factor (dimensionless) for a key radionuclide and T is the travel time (years) of the ground water from the engineered-barrier system to the accessible environment under post-waste-emplacement conditions. For other transport mechanisms, such as diffusion, T_i would be estimated on the basis of other factors.

In general, the travel time of any key radionuclide depends on (1) the chemical and physical properties of the rock insofar as they may relate to the capability to retard the migration of radionuclides, and (2) the mechanism of radionuclide transport through the natural barriers under post-waste-emplacement conditions.

The two performance factors F and T_i offer a simple and direct way, though approximate, to relate site characteristics to estimates of releases to the accessible environment. For example, if the characteristics of the ground water flowing through the repository result in a value of 0.01 for the parameter F during the first 10,000 years, the cumulative release to the accessible environment can be estimated conservatively to be about 1 percent of the EPA release limits (assuming that ground water is the only transport medium). Similarly, if a substantial fraction (say 90 percent) of the pathways through the natural barriers have radionuclide-travel times longer than 10,000 years, then only a fraction (10 percent in this example) of the radionuclide inventory can possibly reach the accessible environment during 10,000 years.

When the two performance factors are considered together, the estimated releases for a site may be lower than those obtained by considering each factor individually. For example, in the first case considered above, F may be found to have a value of 0.01 because of favorable geochemical and ground-water-flux conditions. This value corresponds to 1 percent of the EPA release limits. Furthermore, suppose that the ground-water-travel time and the radionuclide-retardation characteristics are such that only 10 percent of the radionuclides released from the engineered-barrier system can reach the accessible environment in 10,000 years. Then the actual release to the accessible environment would be less than 0.1 percent of the EPA release limits.

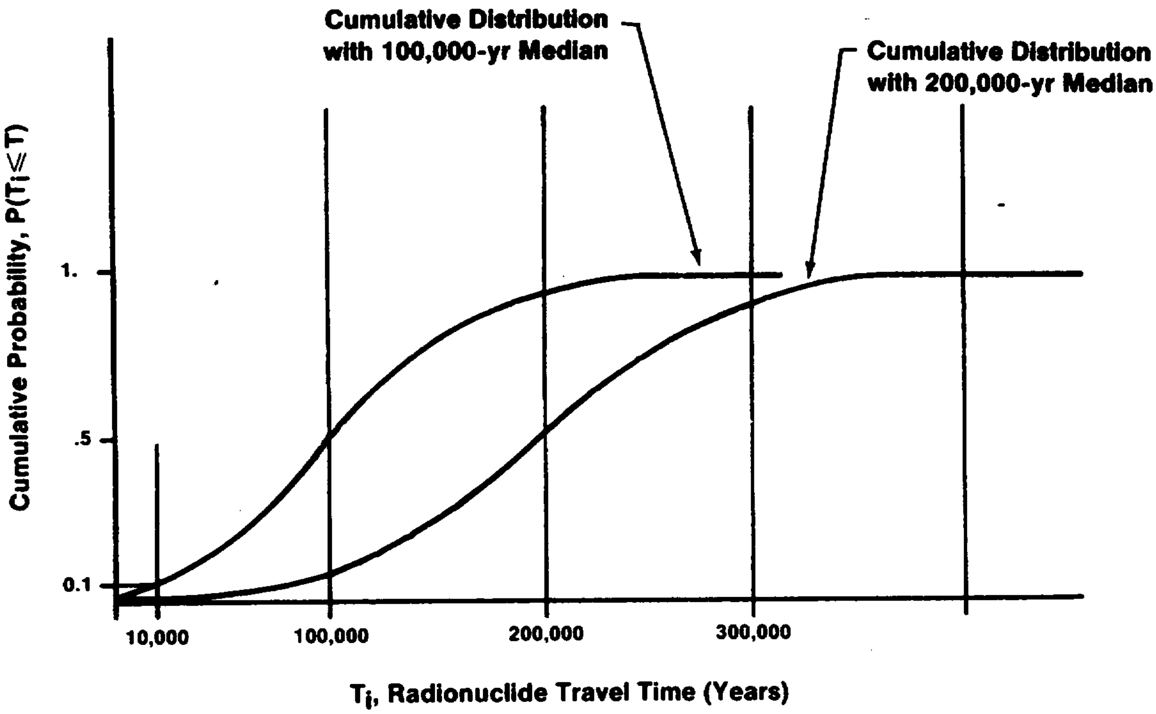

Figure B-5. Illustration of relationship between median radionuclide travel time and fraction of released radionuclides reaching accessible environment.

The actual distribution of the travel times required to quantify T_i is a site-specific factor that is not easily estimated before site characterization. However, the total distribution need not be known in detail in order to determine the effect on releases. For example, as illustrated in Figure B-5, the important information is the portion of travel paths with travel times of less than 10,000 or 100,000 years. A conservative analysis could indicate that the travel-time distribution has such characteristics that, if the median travel time is 100,000 years, about 10 percent of the radionuclides released from the engineered-barrier system would reach the accessible environment in 10,000 years (and 50 percent in 100,000 years).

Similarly, if the median travel time is 200,000 years, then about 1 percent of the radionuclides released from the engineered-barrier system would be released to the accessible environment in 10,000 years and about 10 percent in 100,000 years. Furthermore, for each additional 100,000 years of travel time, the fraction of radionuclides released to the accessible environment in the specified period decreases by an order of magnitude. The actual distribution may provide a smaller fraction of the pathways with travel times of less than 10,000 years or 100,000 years; however, these assumptions are considered to provide a reasonable and conservative basis for the evaluation of releases.

Table B-1. Scores for the first performance measure on the basis of cumulative releases for the first 10,000 years after repository closure

T_t (median travel time of key radionuclides to accessible environment) (years)	F (fraction of radionuclides dissolved in ground water during the first 10,000 years as multiple of EPA release limits)										
	10	3.2	1	0.32	0.1	0.03	0.01	0.003	0.001	0.0003	0.0001
0	0	1	2	3	4	5	6	7	8	9	10
50,000	1	2	3	4	5	6	7	8	9	10	
100,000	2	3	4	5	6	7	8	9	10		
150,000	3	4	5	6	7	8	9	10			
200,000	4	5	6	7	8	9	10				
250,000	5	6	7	8	9	10					
300,000	6	7	8	9	10						
350,000	7	8	9	10							
400,000	8	9	10								
450,000	9	10									
500,000	10										

There are many combinations of F and T_t that, together, result in equivalent system performance with respect to releases to the accessible environment over a given time period. Examples of such combinations are given in Tables B-1 and B-2 for the two performance measures. For example, in the case of a site in which F is equal to 0.01 over 10,000 years because of a moderate quantity of ground-water flow past the waste and favorable solubility limits, the associated score for that performance measure is at least 6, regardless of the radionuclide-travel time at the site. If, in addition, the median value of T_t is 100,000 years, the fraction of the dissolved radionuclides reaching the accessible environment is assumed to be about 10 percent; therefore, the release to the accessible environment would correspond to 0.001 of the EPA release limits. Therefore, the site would receive a score of at least 8. A site with the above characteristics is essentially equivalent to another site with F equal to 0.1 and a median value of T_t equal to 200,000 years. The potential tenfold increase in the dissolution of waste is compensated for by a longer median radionuclide-travel time. Since the release to the accessible environment would be about 0.001 of the release limits, this site would also receive a score of about 8.

The performance factors F and T_t were developed for the purpose of estimating repository performance on the basis of available information for the important characteristics of a site. To this point, the performance of the engineered-barrier system has not been addressed. Impacts of site characteristics on the engineered-barrier system can be taken into account most conveniently by considering the waste-package lifetime. In estimating F, the quantity of radionuclides dissolved in the ground water during the first 10,000 years will be affected by the length of time that the disposal container remains intact or by the quantity of water remaining for waste dissolution after the container-corrosion process is substantially complete. Likewise, the time delay before radionuclides reach the accessible environment depends on container lifetime and the time of radionuclide travel through the controlled zone. Thus, for site evaluations against the performance measures, estimates of F and T_i can be revised by expert judgment to reflect the potential benefits of the waste package in restricting radionuclide releases.

Careful judgment must be exercised in applying Tables B-1 and B-2 to obtain site scores from site characteristics. For example, the distributions used in the preliminary evaluations of travel time in Chapter 6 of the EAs are consistent with the assumptions given here; however, it is entirely possible that the actual travel-time distributions vary appreciably from those obtained with the assumed models of ground-water flow. It is certainly possible that releases estimated by using F and the median value of T_i may be underestimated or overestimated by a factor of 10 or more. Nevertheless, in spite of this uncertainty, this approach provides a useful association between site characteristics (right-hand side) and radionuclide releases (left-hand side) on the performance-measure scales.

Table B-2. Scores for the second performance measure on the basis of cumulative releases between 10,000 and 100,000 years after repository closure

T_i (median travel time of key radionuclides to accessible environment) (years)	F (fraction of radionuclides dissolved in ground water in 100,000 years as multiple of 10,000-year EPA release limits)										
	100	32	10	3.2	1	0.32	0.1	0.32	0.01	0.003	0.001
0 to 10,000	0	1	2	3	4	5	6	7	8	9	10
50,000	0	1	2	3	4	5	6	7	8	9	10
100,000	0	1	2	3	4	5	6	7	8	9	10
150,000	1	2	3	4	5	6	7	8	9	10	
200,000	2	3	4	5	6	7	8	9	10		
250,000	3	4	5	6	7	8	9	10			
300,000	4	5	6	7	8	9	10				
350,000	5	6	7	8	9	10					
400,000	6	7	8	9	10						
450,000	7	8	9	10							
500,000	8	9	10								
550,000	9	10									
600,000	10										

There are two additional points concerning the use of Tables B-1 and B-2 that should be mentioned. First, the performance factor T_1 used in estimating a score in the tables is the median travel time for key radionuclides. Estimates of ranges in the score should therefore be based not on the range of travel times but on the range of <u>median</u> values that could result from alternative conceptual models and conditions. Second, for scenarios leading to direct releases to the accessible environment, such as human intrusion or volcanism, the use of the left-hand scale of a performance measure may be the most appropriate approach to arrive at a score, rather than the use of surrogate measures like F and T_1. In such cases, Tables B-1 and B-2 would not be used.

B.3.3 EXAMPLE APPLICATIONS OF THE PERFORMANCE MEASURES

To demonstrate the use of the performance measures in site evaluations, this section presents three examples: (1) the generic sites used by the EPA in the development of 40 CFR Part 191, Subpart B; (2) a hypothetical repository in the Carrizo sandstone aquifer of south Texas; and (3) the five nominated sites in relation to the performance-assessment results for each.

The examples are included to address comments by the Board on Radioactive Waste Management of the National Academy of Sciences on portions of this report submitted for review on March 17, 1986. In particular, the Board made two recommendations. First, it suggested that the DOE show the postclosure results that would be obtained with the methodology for a repository at a site with poor geohydrologic characteristics. Second, the Board recommended that the DOE compare results obtained with the methodology against results calculated for generically similar sites considered by the EPA in the development of its final standards and against results calculated with performance-assessment models.

<u>Example 1: generic sites considered by the EPA</u>

The first example is the set of cases considered by the EPA in developing the containment requirements of 40 CFR Part 191, Subpart B. Specific cases for hypothetical repository systems in generic basalt, bedded-salt, tuff, and granite sites are described in the background-information document for the final EPA rule (EPA, 1985b). Using specified site characteristics and repository descriptions, cumulative releases to the accessible environment during the first 10,000 years after closure were calculated with the REPRISK code (Smith et al., 1982). In addition, relationships between predicted releases and associated health effects were used to help determine the release limits specified by Table 1 of Appendix A of 40 CFR Part 191.

The EPA did not evaluate releases for the period 10,000 to 100,000 years after closure, and therefore only the first performance measure is considered here. Table B-3 summarizes the application of the performance measure to the the four generic sites. The first row gives the health effects and the second row gives the cumulative releases leading to these health effects, as computed by the EPA. The third row gives the scores that would be assigned to each of these cases by directly relating the calculated cumulative releases to the left-hand side of the performance measure in Figure B-3.

The scores given in Table B-3 could be used to compare these generic sites if the model predictions were adequate to address site performance, including the uncertainties in conceptual models and site parameters. Premature reliance on such model predictions can be avoided by scoring the sites against the right-hand side of the performance measure of Figure B-3. The site parameters (F and T_1) required for this evaluation are given in the fourth and the fifth rows of Table B-3. These parameters were derived from the characteristics for the generic cases specified by the EPA (1985b). The scores associated with these parameters, as estimated from Table B-1, are given in the sixth row of Table B-3.

Comparison of the scores obtained by the two approaches shows that, for the four generic sites, scores based on the parameters F and T_1 provide a

Table B-3. Performance-measure scores for EPA generic sites[a]

Parameter	Basalt	Bedded salt	Tuff	Granite
	SCORES OBTAINED BY EPA METHOD			
Health effects[b]	97	0	0	180
Cumulative release[c]	0.15	0	0	0.32
Score based on the left-hand side of Figure B-3[d]	4	10	10	3
	SCORES OBTAINED BY DOE METHOD			
F value[e]	0.6	0	0.6	0.6
T_1 value[e] (years)	1.1×10^5	2.5×10^6	2×10^6	5×10^3
Score based on the right-hand side of the performance measure for first 10,000 years[f]	4-5	10	10	2-3

[a]Examples from the background-information document for the EPA final rule (EPA, 1985b, Table 8.10-1)
[b]Predicted premature deaths from cancer in 10,000 years for 100,000 MTHM.
[c]Multiple of the EPA release limits computed from Table 7.8-3 of the EPA background-information document (EPA, 1985b).
[d]Estimated from the predicted releases and the left-hand side of Figure B-3.
[e]Based on the characteristics of the generic sites considered by the EPA (EPA, 1985b).
[f]Estimated from Table B-1 and the right-hand side of the Figure B-3.

reasonably conservative measure of performance in terms of predicted releases. Although the generic sites are described in extremely simple terms, relying on one-dimensional effective-parameter representations for the elements of the system, the comparison provides some confidence that the performance measure can be useful in evaluating real sites.

Example 2: Carrizo sandstone aquifer of south Texas

The second example pertains to an actual geologic formation, a formation believed to be geologically unsuitable for a repository: the Carrizo sandstone aquifer of south Texas. Because of its importance as a water supply, this formation has been intensely studied for over 50 years (Klempt, Duffin, and Elder, 1976). Furthermore, trace concentrations of carbon-14, uranium-234, and uranium-238 in the ground water have been investigated for the validation of predictive models to be used in the evaluation of geologic repositories (Andrews and Pearson, 1984), and much of the information needed to apply the performance measure is available.

For the purpose of an illustrative example only, a hypothetical repository is assumed to be sited in the Carrizo sandstone formation. Hydrologic and geochemical data from the analysis by Andrews and Pearson (1984) are summarized in Table B-4. These same data were used to derive the F and T_1 factors. To compute F, it was assumed that the dissolution of radionuclides into the moving ground water is controlled by the solubility of the uranium dioxide ceramic waste form. It was further assumed that the effective cross-sectional area for 1000 MTHM of spent fuel emplaced in the repository is 10,000 m^2. The applicable radionuclide inventories are given in Table 3.3.8 of an earlier DOE document (DOE, 1979).

Values for the performance factors F and T_1 are given in Table B-4. The value of F ranges from 0.2 to 2000. If the key radionuclides are retarded very little, such as for carbon-14, the estimated release to the accessible environment would range from 0.2 to 2000 times the overall release limits of the EPA standards. If the transport velocity of the key radionuclides is similar to that of uranium, then the estimated releases would range from 0.02 to about 1000 times the overall release limits. For a release of 0.02 times the EPA limits, the Carrizo aquifer would score between 5 and 6 on the performance mea-

Table B-4. Parameters used in the evaluation of the Carrizo sandstone aquifer[a]

Hydrologic parameters	
Darcy velocity (m/hr)	0.6 to 1.0
Effective porosity	0.3 to 0.4
Ground-water velocity (m/yr)	1.5 to 3.3
Geochemical parameters	
Solubility of uranium (g/m^3)	10^{-6} to 10^{-3}
Retardation factor	
Carbon-14	1
Uranium	20 to 30
Performance parameters	
F	0.2 to 2000
T_1 (years)	
Carbon-14	2000 to 3000
Uranium	30,000 to 100,000

[a] From Andrews and Pearson (1984).

sure for the first 10,000 years, according to Figure B-3 and Table B-1. Conversely, a release of 1000 times the EPA limits would give a score of -4 by extrapolation of Figure B-3 and Table B-1. If this latter situation were indeed the case, the Carrizo aquifer would be clearly unacceptable for a geologic repository.

Example 3: Nominated sites in relation to performance-assessment results

The third example involves the performance assessments used to evaluate the suitability of the nominated sites in Section 6.4.2 of the EAs (DOE, 1986a-e). These assessments yielded predictions of radionuclide releases on the basis of preliminary conceptual models and available data for the site characteristics and conditions. The models have not been validated and represent varying levels of development. The applications have ranged from bounding analyses to more-detailed evaluations that exclude the effects of the heat emitted by the waste. The results are useful for indicating the general trends to be expected at particular sites, but are not adequate for detailed and meaningful comparisons between and among sites. In part, the purpose of considering the performance-assessment results for the nominated sites as an example is to compare the scores obtained from the performance measure for 10,000 years against those obtained for the generic sites evaluated by the EPA.

Two separate cases were considered in Section 6.4.2 of the EA for each site. One case is referred to as the "performance-limits" case, in which all waste packages are assumed to fail at 300 years and the fractional rate of release from the engineered-barrier system is specified as one part in 100,000 per year. Thus, this case is analogous to the simple generic case evaluated by the EPA and presented in Table B-3. The results for the nominated sites are summarized in Table B-5 for both the first 10,000 years and for the period 10,000 to 100,000 years. These results suggest that the releases are expected to be generally smaller than those for the EPA generic sites and the scores are expected to be correspondingly higher.

This trend is also observed for the second case evaluated in the EAs. The second case (referred to as the "nominal" case) does not arbitrarily specify engineered-system performance, but takes into account the expected impacts of site characteristics and conditions on the engineered-barrier system. The releases predicted for this case are given in Table B-6. These values suggest that, indeed, the performance-measure scores for the nominated sites are expected to be high, with very small releases projected on the basis of the available information. It is to be noted that the nominal case considered in the evaluations in Appendix D is somewhat more general than the nominal case considered in Section 6.4.2 of the EAs and in Table B-6 and takes into account a wider range of uncertainty in site characteristics, conditions, and conceptual models than does Section 6.4.2 of the EAs. Thus, it is possible that scores for the site evaluations in Appendix D may range to values lower than those shown in Table B-6.

Summary remarks

There are some important features of the scoring evaluations that can be identified from the results of these examples. First, a site characteristic that is used to estimate the score is the median time of ground-water travel.

Table B-5. Predicted releases and corresponding performance-measure scores for the performance-limits case for nominated sites

Period	Performance measure	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mt.
10,000 years	Release[a]	0	0	0	0	<0.0002
	Score[b]	10	10	10	10	10
10,000–100,000 years	Release[a]	0	0	0	0.32[c]	0.035
	Score[b]	10	10	10	5	7

[a]Releases expressed as multiples of the EPA release limits in 40 CFR Part 191, Subpart B.

[b]Scores estimated from the performance measures of Figures B-1 and B-2.

[c]The environmental assessment for the Hanford site (DOE, 1986c) reports distributions of releases. The median value is shown in this table. The high value (95% confidence level) is 1.2 for the first 10,000 years and 1.0 for the period 10,000 to 100,000 years. The corresponding scores are 2 and 4, respectively. The low value (95% confidence level) is zero in each case.

Table B-6. Releases predicted for the nominal case in the environmental assessment[a] and corresponding performance-measure scores

Period	Performance measure	Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mt.
10,000 years	Release[b]	0	0	0	0[d]	$<10^{-7}$
	Score[c]	10	10	10	10	10
10,000–100,000 years	Release[b]	0	0	0	0.29[d]	1.8×10^{-7}
	Score[c]	10	10	10	5	10

[a] See Section 6.4.2 of the environmental assessment for each site (DOE, 1986a–e).

[b]Releases expressed as multiples of the EPA release limits (Table 1 of Appendix A of 40 CFR Part 191).

[c]Scores estimated from the performance measures of Figures B-1 and B-2.

[d]The environmental assessment for the Hanford site (DOE, 1986c) reports distri-
butions of releases. The median value is shown in this table. The high value (95% confidence level) is 0.045 for the first 10,000 years and 0.45 for the period 10,000 to 100,000 years. The corresponding score is 5 in each case. The low value (95% confidence level) is zero in each case.

The EPA calculations, for example, are purely deterministic and do not take into account the distribution in travel time because of spatial variations in parameters and other factors that are expected for real sites.

The performance measure takes into account the fact that there may be travel times substantially shorter than the median value. In particular, because some radionuclides may be released before 10,000 years even if the median value is much greater than 10,000 years, use of the performance factors will generally provide lower scores (greater cumulative releases) than those resulting from deterministic calculations based on mean parameter values. This explains, in part, why in Table B-3 the scores based on the performance measure are in some cases lower than those based on the EPA calculations of radionuclide releases. In the evaluations of real sites, the median travel times should be used rather than the full range of travel times. Ranges in scores may result, however, if there are ranges in these median values resulting from different conceptual models or site conditions.

The second point is that the scoring methodology can accommodate more complex travel paths than those described in the simple cases considered by the EPA (1985b). In addition, it is not necessary to use the overly conservative approximation applied for the REPRISK calculations--that is, the volume of water that dissolves radionuclides is the entire volumetric flow crossing the host rock within the confines of the repository in 10,000 years. Only a fraction of this volume may be taken into account in the determination of the Q values required to calculate F. For example, it may be appropriate to consider only the water that is in contact with the waste package or the flux that intercepts an effective cross-sectional area containing the waste package. In the scoring of real sites, an effective area of about 30 m^2 per package was used.

Finally, there are cases in which it may be more appropriate to use the left-hand side of the performance measure rather than the right-hand side. For example, in scenarios involving direct releases of radionuclides, like those initiated by human intrusion or volcanic activity, the releases themselves can be evaluated directly (i.e., in terms of the fraction of the repository or package inventory that is released as a result of the disruption) and used to derive a score. In such cases, Tables B-1 and B-2 would not be used.

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Appendix C

DEVELOPMENT AND DESCRIPTION OF POSTCLOSURE SCENARIOS

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Appendix C

DEVELOPMENT AND DESCRIPTION OF POSTCLOSURE SCENARIOS

C.1 INTRODUCTION

This appendix describes the potentially significant scenarios that could lead to releases of radionuclides to the accessible environments at the various nominated sites. The scenarios are based, in general, on the known and expected characteristics of the sites and their geologic settings, as well as the generic features and conditions of the host-rock types and repository systems under consideration in this comparative evaluation. Initially, a broad collection of scenarios was identified, using information from the literature and the environmental assessments (EAs) for the nominated sites. By means of a screening process, the number of scenarios was gradually reduced to a credible set. In this process, particular attention was given to any scenarios that reflected in whole or in part any potentially adverse conditions identified at the sites. The criteria for the removal of a scenario from the initial collection were as follows:

- The impact of the postulated set of conditions and processes or sequence of events on the expected repository performance is such that the expected releases to the accessible environment are not increased by more than ten percent; or

- The likelihood of occurrence of a postulated set of conditions and processes or sequence of events is less than one chance in 10,000 over the first 10,000 years after repository closure.

Because of the manner in which the performance measures relate site characteristics to releases, the first criterion is reflective of significant changes in site characteristics (e.g., total volume of ground water in contact with the waste) and performance factors (e.g., radionuclide travel time) that are important to releases from the engineered-barrier system and transport through the natural barriers. The second criterion is based on guidance for implementation of 40 CFR Part 191, Subpart B, as specified in Appendix B of that regulation.

These criteria were applied first to specific processes and events and then to scenarios involving site-specific factors and information. To ensure that low-probability scenarios producing very large effects were not screened out, the product of the probability of the scenario and the factor by which it was estimated to increase risk was calculated. In no case was this product found to be significant for a scenario that was screened out.

Three different classes of scenarios were considered:

- Nominal case (expected conditions)
- Unexpected features
- Disruptive processes and events

The nominal case is based on the expected geohydrologic, geochemical, and rock conditions. The natural variability in these characteristics and the range of uncertainty that presently exists are taken into account. In addition, these conditions include natural changes that are expected at the sites. For example, the influence of expected climatic changes over the next 100,000 years on the geohydrologic system is considered. The influence of the excavation and the effect of the heat generated by the emplaced waste on the thermal, fluid, and chemical conditions are also considered.

The second class of scenarios includes the effects of unexpected features at the site. These features are not expected to be present, but they cannot be completely ruled out on the basis of the site information that is presently available. For example, an unexpected degree of subsidence or thermal expansion of the rock mass above the underground facility or geologic features that have not been detected (e.g., undetected breccia zones or undetected faults) could lead to extreme impacts on the expected performance of the repository.

The third class of scenarios includes processes and events that could lead to a disruption of the repository during the next 10,000 years. The potentially disruptive processes and events considered here include those related to erosion, dissolution, tectonic activity (including magmatic activity), and human interference. (As mentioned above, climatic changes are included as part of the nominal-case scenario (expected conditions).) Premature failures of the waste packages and the shaft and repository seals are also considered in this class of scenarios.

The probabilities of the three classes of scenarios are illustrated in Figure C-1. This figure shows the hypothetical probability distribution function for cumulative releases, y, at a typical site. The distribution of values is a result of variations in site characteristics, uncertainties in conditions, and the effects of disruptive processes and events. This distribution function is resolved into two components in Figure C-1. The first component, shown in the upper curve, represents the effects of expected conditions and the effects of unexpected features and accounts for most of the probability distribution. The division between expected conditions and unexpected features is shown as y_{max} in the figure. The portion of the first component ranging from $y = 0$ to $y = y_{max}$ is designated the nominal case. The total cumulative probability of the range is P_N. The remainder of the first component, representing the unexpected features, has a total probability of P_U.

The second component, shown in the lower curve, includes the effects of disruptive processes and events. The distribution for the second component has a total probability of P_D corresponding to the sum of the probabilities of the two disruptive-event scenarios in this example--that is, $P_{D1} + P_{D2}$. The total probability is

$$P_N + P_U + P_D = 1.$$

Since P_U, P_{D1}, and P_{D2} can be estimated on the basis of expert opinion, the probability of the nominal-case scenario is simply

$$P_N = 1 - P_U - P_D.$$

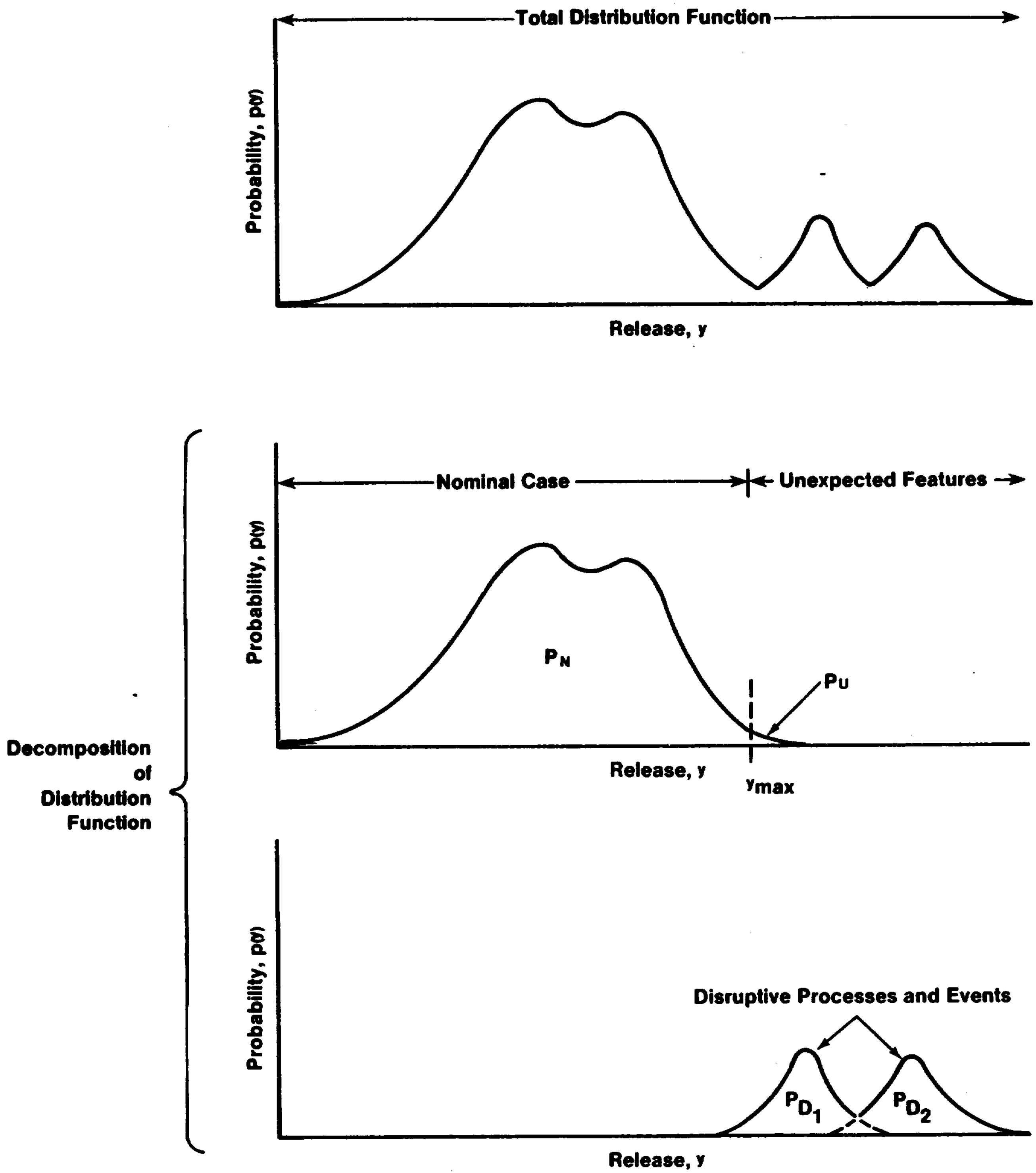

Figure C-1. Decomposition of the consequence probability distribution function.

This representation of the risk curve for a particular site is admittedly schematic; nevertheless, it illustrates the scenario classes described in more detail later.

C.2 APPROACH TO THE SCREENING AND DEVELOPMENT OF SCENARIOS

The general approach to the screening and development of the scenarios for this analysis is illustrated in Figure C-2. The first step is to establish the nominal case. This case is based on the current understanding of site characteristics and conditions, such as those described in Sections 6.3 and 6.4 of the environmental assessments for the nominated sites (DOE, 1986a-e), and takes into account the changes that are expected to occur in these conditions because of waste emplacement. The nominal case is based on the site factors and conditions that relate to the release of radionuclides from the engineered-barrier system and transport through the natural barriers.

The next step is to review all of the potentially disruptive processes and events induced by nature and humans and unexpected features that could affect site performance. A preliminary screening of these processes, events, and features is conducted in terms of the probability of occurrence. Those with a probability of less than 1 chance in 10,000 over 10,000 years are not considered credible and are eliminated from consideration unless the consequences could be large.

The next step is to construct scenarios in terms of the specific effects of potentially disruptive processes and events and unexpected features on expected repository performance. These steps result in a set of potentially significant scenarios that can be evaluated in terms of site-specific characteristics and conditions.

C.3 NOMINAL CASE (EXPECTED CONDITIONS)

C.3.1 INTRODUCTION

The analysis of the nominal case at each site is discussed in Section 6.4.2 of the EA for the site (DOE, 1986a-e). This discussion indicates, for example, that the waste is expected to be contained within the waste packages emplaced in the repository. Corrosion and other degradation processes are expected to occur, and it is possible that at some time the waste packages will fail, allowing ground water to come in contact with the waste. Radionuclides can then be leached from the waste form, dissolved in the ground water, and released from the engineered-barrier system. The released radionuclides can then be transported to the accessible environment by diffusion through the rock or by advective transport in ground water.

Under these conditions, the performance factors that are important include the amount of waste that can be dissolved into the ground water and the time of radionuclide travel through the natural barriers. The waste-package lifetime could also be important if it is comparable to, or greater than, the radionuclide-travel time. More-detailed understanding of the site

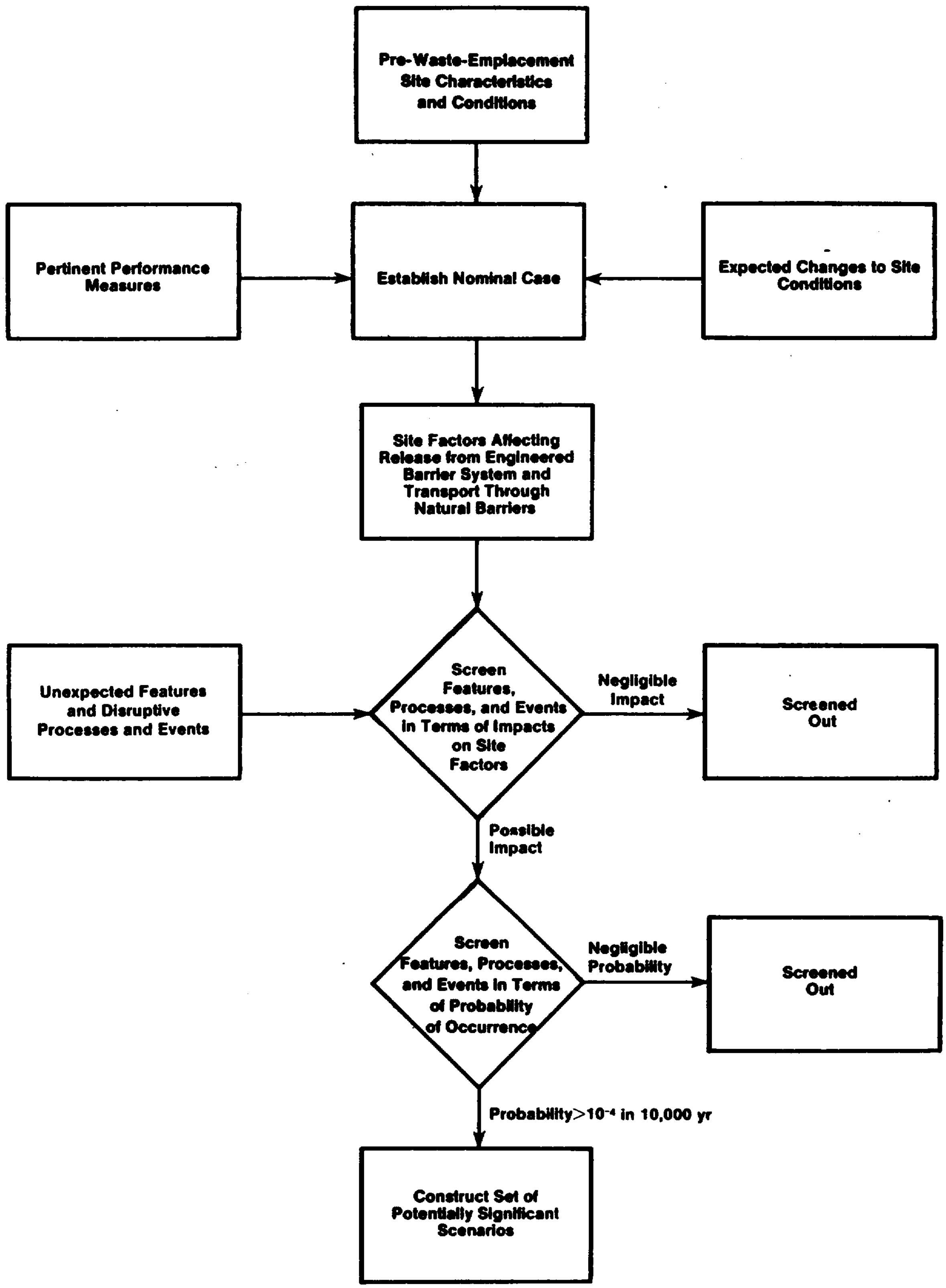

Figure C-2. General steps in the screening and development of scenarios.

after characterization could reveal that there are other important factors; however, on the basis of what is now known about each site, these two factors are considered to be the most important under expected conditions.

The specific conditions and site characteristics affecting the performance factors in the nominal case are summarized in Table C-1. These include the expected thermal, mechanical, geohydrologic, geochemical, and other conditions resulting from the pre-waste-emplacement characteristics of the site, the natural changes in these characteristics, and the changes induced by the excavation of the repository and the emplacement of heat-generating wastes.

For example, waste-package containment depends on the thermal, mechanical, fluid, chemical, and radiation conditions in the repository. Local thermal conditions affect waste-package degradation rates and local chemical and fluid conditions. Local temperatures depend, in turn, on the natural thermal environments at the site and the temperature increases resulting from waste emplacement. The important parameters that determine these conditions include

Table C-1. Site conditions and characteristics affecting repository-performance factors

1. Conditions affecting waste-package lifetime
   a. Thermal conditions
   b. Mechanical conditions (thermomechanical stresses, ground movement)
   c. Volume of, and replacement rate for, fluids near waste package
   d. Corrosion rate
2. Local fluid conditions affecting the rate of release from the engineered-barrier system
   a. Ground-water flux through the host rock or seepage into repository
   b. Number of packages exposed to water
3. Local chemical conditions affecting the rate of release from the engineered-barrier system
   a. Radionuclide solubility
   b. Waste-form dissolution rate
   c. Thermal effects on leach rates and local chemical conditions
4. Conditions affecting ground-water movement to accessible environment
   a. Rock characteristics that determine ground-water pathways
   b. Hydraulic properties
   c. Head gradients
   d. Unsaturated flow characteristics
   e. Constraints due to regional flow conditions
5. Conditions affecting retardation
   a. Sorption
   b. Precipitation
   c. Physical retardation
   d. Dispersion
6. Other conditions affecting radionuclide-travel time
   a. Diffusion transport
   b. Transport of gases

the thermal properties of the rock and the density of the waste in the repository. Likewise, the performance of the waste package is affected by local mechanical conditions, including the stresses imposed on the package by the rock. These conditions depend on the natural state of stress in the rock before excavation and the changes in the stresses in the rock induced by repository excavation and the heat generated by the waste. Similarly, the fluid and chemical conditions can affect the rate at which waste-package components corrode.

The release of radionuclides from the engineered-barrier system is also affected by local site conditions. For example, the waste-dissolution rate depends directly on the amount of water in contact with the waste, which depends on both the local flux through the repository and the amount of waste actually exposed to the water. If natural conditions or engineered barriers restrict the amount of ground water that can actually come in contact with the waste, effects on the dissolution of waste may be limited. The fluid conditions are determined by the natural flux of ground water through the host rock, the pathways created by the excavation of the repository, and the effects of local thermal conditions on the flow.

Local chemical conditions will also influence the degree of waste dissolution. The key geochemical parameters include those that control the amount of radionuclides that can be dissolved in the ground water and the rate of waste-form dissolution. These depend in turn on the solubility of the waste matrix and interactions between the waste form and the ground water.

The principal conditions affecting the transport of radionuclides through the geohydrologic system are the movement of ground water to the accessible environment and the retardation of the radionuclides in relation to the ground-water flow. The movement of the ground water depends on the existing pathways for the water (e.g., through fractures and joints or through the porous rock matrix), hydraulic properties (e.g., hydraulic conductivity and effective porosity), and the local head gradients. The movement of water within the controlled area is also determined by the regional pressure distribution and by the ability of surrounding geohydrologic units to receive and transmit water. Finally, flow conditions within the controlled area may be influenced by the heat generated by the waste. For sites in which ground-water flow in the unsaturated zone is important, water content or rock-matrix characteristics are also important. In either unsaturated or saturated flow, the key parameters for this evaluation include the ground-water-travel time and the flux of water along ground-water pathways.

The retardation of radionuclides is controlled by chemical and physical processes. Chemical retardation results from the sorptive characteristics of the minerals along ground-water pathways. In addition, radionuclides may precipitate from the ground water during transport through the natural barriers. Matrix diffusion and other physical processes also contribute to the retardation of radionuclides during transport. The dispersion of radionuclides in the ground water can occur because of molecular diffusion during transport, variations in hydrologic properties over the transport pathway, and other effects. Finally, factors other than advective transport can contribute to radionuclide-travel time. For example, in aquitards (beds with little or no measurable movement of water), transport by diffusion could be more important than advection. For volatile elements like krypton and iodine, vapor-phase transport could be significant.

The nominal case also depends on (1) the design and the expected behavior of the waste package and engineered-barrier system and (2) expected climate changes. These factors are considered below.

C.3.2 EXPECTED BEHAVIOR OF WASTE PACKAGES

Failure of most of the waste packages is not expected to occur for at least 1000 years at all sites. However, some packages may be flawed or may be damaged during the operational period. Other packages could be emplaced improperly so that they are subjected to conditions different from the design basis. Corrosion rates could be higher than those considered in preliminary projections based on short-term tests and estimates based on a uniform corrosion model. The evaluations for the nominal case in the EAs have included wide corrosion-rate ranges that take into account the range of uncertainty in this regard. Therefore, early failure of a small fraction of the waste packages cannot be precluded. As reported in Section 6.4.2 of the EAs (DOE, 1986a-e), analyses based on the assumption of early failure for some of the waste packages have also been conducted.

C.3.3 EXPECTED BEHAVIOR OF SHAFT AND REPOSITORY SEALS

The function of the seals is to limit the intrusion of water into the underground openings and restrict the migration of radionuclides along preferential paths created by the openings or the shafts. Leakage through the seals would not necessarily be significant if it is comparable to, or less than, the seepage expected to occur through the undisturbed rock. The analyses in the EAs have considered a wide range of hydraulic properties of the rock in their evaluation of expected conditions; for example, variations of several orders of magnitude have been considered in accounting for the heterogeneity of the rock. The properties expected for the seals are expected to fall well within these ranges. Therefore, ranges in the performance of the seal system are implicitly taken into account in the nominal case.

C.3.4 EXPECTED CLIMATIC CHANGES

Worldwide climatic changes are expected over the next 100,000 years. For example, minor variations in the earth's orbit have led to past changes in the seasonal distribution of solar insolation and appear to have initiated glacial cycles. It is believed that, over the next 23,000 years, perturbations from orbital variations may lead to a cooler climate with a trend toward enlarged continental ice sheets (Imbrie and Imbrie, 1980). This current cooling trend could produce a period of maximum glaciation in about 45,000 to 60,000 years (Craig et al., 1983; Spaulding, 1983). A minor glacial stage may occur about 15,000 to 23,000 years from now (Craig et al., 1983; Spaulding, 1983).

Glaciation could conceivably be important for waste isolation. For example, renewed continental glaciation could affect the repository if the stress state of the rock is affected by loading and unloading as the ice sheet advances and recedes over the site. If an ice sheet advanced to the recharge or drainage basins of the sites, the deep ground-water system might be affected. For one site, the Hanford site, such effects were evaluated in Section 6.3.1 of the EA (DOE, 1986d). Even taking into account impacts on erosion and recharge, it was concluded that the effects would be insignificant. At the other sites, glaciation is not likely to occur. It is generally accepted that the ice cover from renewed glaciation in the next 100,000 years will be confined to the regions that were covered with ice during the Pleistocene. Since none of these sites was glaciated during the Pleistocene, direct cover of any of the sites is not likely in the next 100,000 years.

A more important effect of climatic change could be attendant changes in rainfall. For example, increased precipitation during a future pluvial period could result in increased infiltration and recharge. These changes may decrease the time of ground-water travel to the accessible environment or increase the flux through the repository. At a repository in the unsaturated zone, an increase in the elevation of the water table, which could result from the increased recharge, could affect the travel time of ground water and the radionuclides dissolved in this water. Increased flux in the unsaturated zone could also be a factor affecting the travel time. New flow paths or modes of flow may result. Retardation may be affected if the flow is diverted to paths with different retardation characteristics. At the salt sites, salt-dissolution rates may be increased because of increased infiltration. The specific effects of a worldwide climatic change are clearly related to the unique geo- graphic features of each site.

A warming trend in the next 10,000 years from increases in atmospheric carbon dioxide could affect precipitation rates at the sites. Modeling predictions of long-term (100,000-year) climatic changes do not account for man-induced effects or the effects of volcanic activity on climatic cycles. However, the impact of such perturbations on the gradual cooling trend of the last 6000 years is not expected to overwhelm the long-term trend toward renewed glaciation and increased rainfall (see, for example, Craig et al., 1983; Imbrie and Imbrie, 1980).

The effects of worldwide climatic changes on the expected conditions that are considered in the nominal case include a potential increase in infiltration and recharge at the sites during a period commencing about 15,000 years after the present. Precipitation can increase by as much as 100 percent during a pluvial period (Spaulding, 1983), and the expected conditions necessarily take into account changes of this order.

C.4 UNEXPECTED FEATURES

C.4.1 INTRODUCTION

The nominal case is based on expected ranges of geohydrologic and geochemical conditions and rock characteristics. It is possible that extreme conditions outside these ranges could arise from the existence of features or characteristics which are not expected at the site but which cannot be unequivocally precluded by the present data. For example, extreme conditions could result from--

- A significant loss of rock-mass integrity because of excavation or the heat generated by the emplaced waste.

- Geologic features not detected at the nominated site.

- Other geohydrologic or geochemical changes in the site or of its response to the heat generated by the emplaced waste.

Extreme responses to repository excavation or waste emplacement include the subsidence or uplift of the rock mass above the underground repository. Extreme subsidence, for example, could cause a disturbance in the rock that could extend from the repository to an overlying aquifer and create preferential pathways for the incursion of water into the repository horizon and for the migration of radionuclides away from the repository.

Undetected geologic features includes those which may be present in similar rock formations elsewhere, but for which no evidence of their existence at the nominated sites has been obtained. The current information regarding the site may not be adequate to rule out such a feature unequivocally. It is possible that some features at the site will not be detected even during site characterization or during repository operation. Indeed, it is not expected that every geologic feature of the site will be characterized. Table C-2 lists some of the features that have been found in rock types like those at the nominated sites and may go undetected. These are described more fully below.

Table C-2. Unexpected features

Rock	Feature
Bedded salt	Small-scale folding Zones of increased porosity Brine pockets Pressurized gas pockets Lateral facies changes Breccia zones Fractures in brittle beds Small-scale faulting
Dome salt	Small-scale folding Zones of increased porosity Brine pockets Pressurized gas pockets Vertical, discontinuous nonsalt features Variations in salt quality
Basalt	Feeder dikes Profuse internal structures Flow pinchout Vertical fracture zones less than 1 meter wide Major fault
Tuff	Minor fault zones (less than 1 meter wide) Significant lateral variations Dikes and sills Vertical heterogeneity

C.4.2 SALT FORMATIONS

Unexpected features common to bedded and dome salt include small-scale folding, zones of increased porosity, brine pockets, and gas pockets. Small-scale folding can result in a significant variation in thickness and elevation, and it can occur over short distances. Because these variations may occur over short distances, they may not be determined from the vertical boreholes at a site. Brine pockets include both large inclusions of water that sometimes occur in the margins of salt domes and in other salt units and the large-scale zones of increased porosity that are saturated with brine and are sometimes associated with folding in salt beds. Gas pockets are zones of increased porosity that have been found in both bedded-salt and dome-salt structures.

Other undetected features that could occur at bedded-salt sites include lateral facies changes, breccia zones, fractures in brittle beds, and small-scale faulting. A lateral facies change can result from the pinching out of strata. Breccia zones are zones of rubble associated with small-scale internal dissolution. Fractures in brittle beds are potential connections across aquicludes or small-scale interbeds that could allow significant amounts of water to reach salt formations. Small-scale faulting refers to faults through the salt formations that, because of inhomogeneities in the salt, are not healed.

In salt domes there can exist vertical, discontinuous, nonsalt features or anomalous zones that separate the lobes of salt. Similarly, variations in the quality of the salt across a dome have been observed.

C.4.3 BASALT FORMATIONS

The possible undetected features at a basalt site include feeder dikes, profuse internal structure within the basalt flows, flow variations and pinchouts, extensive vertical fracture zones, or an undetected major fault. Feeder dikes are the channels through the basalt that provide the source for an overlying basalt flow. Profuse internal structures in a flow can include vesicular zones, spiracle zones, pillow zones, or other anomalous zones. Flow pinchouts are basalt-flow terminations. Vertical fracture zones are fractures that are not detected but could lead to conditions not taken into account under the expected conditions. Similarly, a major fault is one that cuts across many formations, is not detected by site characterization, and could be a significant pathway to the accessible environment.

C.4.4 TUFF FORMATIONS

The possible undetected features in tuff include minor fault zones, significant lateral variations in strata, dikes and sills, and vertical heterogeneity. Although faults are already known at the site, it is conceivable that there could be undiscovered faults that may have a significant impact on expected performance. Likewise, there may be variations within the tuff units--for example, in thickness and extent or in the presence of lithophysal cavities.

Intrusive structures like dikes or sills could be undetected. There may be vertical variations in properties that could lead, for example, to perched-water zones and could affect expected repository performance.

C.4.5 OTHER UNKNOWN FEATURES

Beyond the features that have not been identified at the nominated sites but are known to exist in similar rock formations elsewhere, there may be other features that are not known or suspected. For example, there could be features that have not yet been considered for the site because of insufficient information. In addition, there may be features that have not yet been considered to be important at any site because there is no experience with the behavior of a repository in deep geologic formations. The potential for such features adds uncertainty to the performance predictions. The factors that could be affected by such unexpected features are listed in Table C-3.

Table C-3. Potential impacts of unexpected features on the predictability of repository performance

ROCK CHARACTERISTICS
Dramatic differences in heat conduction in comparison with expected conditions
Dramatic differences in mechanical strength and deformation
GEOHYDROLOGY
Differences in ground-water flow mechanisms in comparison with expected conditions
Dramatic differences in ground-water flow paths
Dramatic differences in hydrologic properties (e.g., permeability, effective porosity)
Dramatic differences in head gradients
GEOCHEMISTRY
Dramatic differences in geochemistry from temperature increases much greater than those expected
Dramatic differences in ground-water geochemistry from new water source
Dramatic differences in the rate and the degree of low-grade metamorphism in rock and backfill
Dramatic departure from thermodynamic equilibrium

Dramatic differences in rock characteristics, such as differences in the thermal or mechanical-strength properties, could give rise to temperatures that are much higher than expected or to an unexpected loss of rock integrity. These phenomena could result in changes in the geohydrologic and geochemical conditions. Large differences in the geohydrologic and geochemical conditions could have important impacts on some performance factors at the site, such as the radionuclide-travel time and the concentration of radionuclides in water.

C.5 DISRUPTIVE PROCESSES AND EVENTS

C.5.1 IDENTIFICATION OF POTENTIALLY DISRUPTIVE PROCESSES AND EVENTS

The adverse effects of any disruptive processes or events that might occur during the next 10,000 years are considered in the comparison of sites. The identification of potentially disruptive processes or events was based on extensive review of the general literature and the reports of investigations and analyses for specific sites. The existing literature refers to a variety of phenomena that could disrupt a repository (Bingham and Barr, 1978; Burkholder, 1980; Claiborne and Gera, 1974; Cranwell et al., 1982; Davis et al., 1980; DOE, 1980, 1983; Giuffre et al., 1980; Harwell et al., 1982; Hunter, 1983; IAEA, 1983; Koplik et al., 1982; Lee et al., 1978; Arthur D. Little, Inc., 1980; Little, 1982; Long, 1980; ONWI, 1985; Pepping et al., 1983; Ross, 1986; Sandia National Laboratories, 1983; Scott et al., 1979; Stottlemyre et al., 1980; Vesely and Gallucci, 1982). The phenomena that are considered for the present analysis are listed in Table C-4. This list includes, for example, those phenomena considered by the International Atomic Energy Agency (IAEA, 1983). As indicated in Table C-4, some of these phenomena (e.g., climatic changes, glaciation, and diagenesis) were taken into account in the considerations of the nominal case. Other phenomena were considered in terms

Table C-4. Phenomena potentially relevant to release scenarios

NOMINAL CASE (EXPECTED CONDITIONS)	
Brine-inclusion migration Buoyancy and convective cells Changes in rock characteristics Climate changes Corrosion Diagenesis	Geochemical changes Geohydrology changes Localized rock fracturing Sea-level changes Thermal effects Thermomechanical effects
UNEXPECTED FEATURES	
Extreme changes in rock characteristics, geohydrology, or geochemistry, induced by excavation or heat generated by waste	Undetected features, such as faults, shear zones, breccia pipes, dikes, gas pockets, boreholes
DISRUPTIVE EVENTS AND PROCESSES	

Brine pockets
Deposition
Diapirism
Dissolution
Epeirogeny
Erosion
Meteorite impact
Severe-weather phenomena
Surface-water changes
Tectonic activity
  Faulting
  Magmatic activity
	Human interference
	  Drilling
	  Ground-water withdrawal
	  Injection
	  Irrigation
	  Military activities
	  Mining
	  Recharge
	  Underground storage
	Premature failure of waste packages
	Incomplete sealing of the shafts and the repository

of unexpected features (e.g., undetected faults). Those conditions not considered in these categories are evaluated under the category of disruptive processes and events.

C.5.2 PROCESSES AND EVENTS OF NEGLIGIBLE LIKELIHOOD OR IMPACT

An initial screening of these processes and events was based on impact on site performance or probability of occurrence. For this analysis, a probability of less than 1 chance in 10,000 over the first 10,000 years was considered to be negligible. The phenomena eliminated in this initial screening are discussed below.

Deposition

The deposition of material on or near a site from erosion elsewhere would increase the thickness of the overburden. Increased loading could conceivably affect the hydraulic characteristics of the site. However, analyses by Arthur D. Little, Inc. (1980) and Cranwell et al. (1982) show that there would be virtually no impact on repository performance. Therefore, this process is not considered to be potentially disruptive to a repository.

Epeirogeny

Epeirogeny involving regional uplifts or downwards may occur in stable cratonic areas. In general such processes are extremely slow and are not likely to lead to significant disruptions of a repository (Arthur D. Little, Inc., 1980; Harwell et al., 1981).

Erosion

The discussions in Section 6.3.1 of the EAs (DOE, 1986a-e) concerning the rate of erosion conclude that ongoing erosional processes do not appear to be significant at any of the nominated sites. For example, Schumm and Chorley (1983) list denudation rates in mountainous regions, such as the Himalayas, of only about 10 meters in 10,000 years. Similarly, rates for valley incision of sedimentary rock in the Colorado River region do not produce more than about 3 meters of erosion in 10,000 years. Such erosion is not expected to significantly affect a repository at least 200 meters below the surface.

Even for locations where uplift is ongoing (typically near subduction zones), erosion after 10,000 years would only amount to a few tens of meters (Schumm and Chorley, 1983). The reviews by Arthur D. Little, Inc. (1980) and Hunter et al. (1983) agree with these conclusions. Because there are no credible erosional processes that could remove sufficient overburden to affect the site conditions that are relevant to the performance measures, no scenarios were developed for repository disruption by erosion.

Formation of new brine pockets in salt

The development of a brine pocket after repository closure has also been considered. For example, brine migration induced by the heat generated by the waste may result in some leakage into the repository. Creep of the salt could then result in pressurization of this brine. However, the analyses referenced in Section 6.4.2 of the EAs for the salt sites (DOE, 1986a-c) indicate that, even for extreme assumptions, the volumes of water involved are insignificant. Larger amounts of water may be available from nearby interbeds, which could result in seepage into the repository if a connection between the interbed and the repository were to develop after closure. However, any such connection could not lead to a brine pocket within the repository because the water would be driven out by the lithostatic pressure induced by salt creep. Therefore, a scenario involving the formation of new brine pockets in salt was not developed.

Salt diapirism

Diapirism is not considered in this evaluation because there is no evidence of significant salt-dome growth at any of the sites under consideration. Furthermore, studies indicate that a salt thickness of more than 300 meters and an overburden of at least 2000 meters are needed to generate diapiric movement (Arthur D. Little, Inc., 1980). Therefore, the process is not considered to be relevant to any of the nominated salt sites.

Meteorite impacts

Meteorite impacts have been considered in many reports (Claiborne and Gera, 1974; Lee et al., 1978; Arthur D. Little, 1980; Koplik et al., 1982; Vesely and Gallucci, 1982). In all cases it was concluded that the probability of impact by a meteorite or other astrophysical body is less than 10^{-11} per square kilometer per year (i.e., approximately 10^{-7} per square kilometer over 10,000 years). This event is therefore not considered to be significant.

Severe-weather phenomena

Meteorological phenomena, such as hurricanes or tornadoes, are not expected to have a direct impact on performance. The surface flooding of the site that could be caused by such storms is not expected to be important, because the effects would be transient and of little or no long-term consequence to the repository. Tsunamis and seiches--wave phenomena associated with large bodies of water--are not of concern because such water bodies have negligible probability of occurrence at the nominated sites during the next 10,000 years.

Surface-water changes

Some reports refer to changes in surface hydrologic conditions that are possible during the next 10,000 years, including the relocation of rivers and streams, the creation of lakes, and the impoundment of waters by landslides, faulting, or engineering modifications. It is not likely that these effects would result in any direct impact on the performance of a repository because the surface-water system at any of the nominated sites does not have a significant connection with the deep geohydrologic system. Furthermore, discharge points for deep waters are not likely to be significantly affected by such changes (Cranwell et al., 1982; Vesely and Gallucci, 1982).

C.5.3 DISSOLUTION

The salt sites may be susceptible to host-rock dissolution. The existence of localized zones of dissolution and dissolution fronts at the salt sites is addressed in Chapters 3 and 6 of the EAs (DOE, 1986a-c). Any ongoing dissolution associated with these zones is not likely to have an impact on repository performance because the sites were purposely selected far enough from known dissolution fronts to avoid any intersection with the controlled area for at least 10,000 years. The existence of large undiscovered zones of dissolution that could advance to the vicinity of the repository is unlikely because dissolution features that expand at even very low rates tend to have abundant surface expression. For example, throughout the Permian Basin, features for advance rates as low as 10 centimeters per year are easily observed. In addition, data from drillhole logs and geophysical surveys in the vicinity of the sites reveal little evidence of zones of active dissolution (e.g., missing beds, major faults).

Repository performance may be adversely affected by disruptive dissolution if the repository is breached by a significant dissolution feature or if ground-water flow paths in the controlled area are affected. Breaching of the repository would greatly increase the amounts of brine available for waste-package corrosion and waste-form leaching, thereby affecting the waste-package lifetime and increasing the amount of radionuclides available for release to the surrounding ground-water system. Breaching the repository would also reduce the long travel times predicted for a salt repository under expected conditions. The interception of flow paths outside the repository could shorten travel times.

It is possible that local dissolution rates may be much higher than the regional averages, or that unexpected disruptions at the site could increase contact between ground water and the host rock. Possible disruptions of this type include climatic fluctuations, tectonic events, the fracturing of confining layers through repository-induced stresses, and human intrusion.

Climatic fluctuations could increase the rate of infiltration into the deep ground-water systems, which could in turn increase the rate of dissolution at the bedded-salt sites. However, as discussed above, such changes would not lead to a disruption of the repository in 10,000 years. Therefore, no scenario was developed for this effect.

A tectonic event like faulting could lead to a disruption of confining layers and increase the accessibility of the host salt to water. Such an event could increase the rate of advance of a dissolution front or could initiate localized dissolution, which could be significant if the fault is in the vicinity of the repository. The likelihood of faulting in the region near the salt sites is discussed later under disruptive tectonic events.

The confining units that separate the salt units from units containing relatively fresh water or unsaturated brines may be fractured. Also, existing rock fractures may open because of the excavation of the repository openings or because of the thermomechanical stresses induced by the heat generated by the waste. Fracturing induced by mining is not expected to be significant at the bedded-salt sites since the disturbance would extend less than a few room diameters into the rock and the confining sequence is hundreds of meters thick.

At the Richton Dome site, the buffer zone of salt between the repository and the flank of the dome is at least 240 meters thick, and hence mining-induced stresses are not likely to affect this zone significantly. Thermally induced stresses may be more important, however, since thermal expansion could disturb the rock at distances that extend beyond the salt. Therefore, the confining units between a host salt bed and an overlying aquifer or the caprock and the sheath that protects a salt dome from surrounding geohydrologic units could be affected. Provided the rate of dissolution is rapid enough, the disturbance could permit increased contact between the water and the host salt, thus leading to local dissolution that could adversely affect the repository. Therefore, such a disturbance was considered in developing the scenarios for disruptive events.

Human intrusion, such as exploratory drilling, could lead to pathways for water from an overlying aquifer down and through the host salt. The processes initiated by such intrusion could also involve localized dissolution and are discussed later under human interference.

Finally, the possibility of local dissolution rates higher than the average rates throughout the geologic setting could imply the possibility of an unexpected breach of the repository. Heterogeneity of the site may lead to irregularities along the leading edge of an advancing dissolution feature and variations in local dissolution rates of up to an order of magnitude. In this case, the advance of a dissolution front could be more rapid than estimates based on the regional averages would suggest. Therefore, scenarios involving an increased rate for the advance of a dissolution front were developed.

C.5.4 TECTONIC ACTIVITY

Tectonic processes include fault movement (both permanent displacement and strong ground motion), magmatic activity, folding, tilting, uplift, and subsidence. The slow, gradual processes of folding and tilting are not likely to lead to a disruption of the repository during the next 10,000 years. However, numerous studies conclude that faulting and magmatic activity are potentially significant (Arthur D. Little, 1980; Stottlemyre et al., 1980; Harwell et al., 1981; Koplik et al., 1982; Cranwell et al., 1982; Davis et al., 1983).

Faulting

The probability of faulting at given sites has been evaluated by many investigators (see, for example, Koplik et al., 1982). The available evidence strongly suggests that most fault movements in the shallow crust have followed existing zones of faulting or zones of weakness (Trask, 1982). On the basis of this evidence, the generation of new faults in unfractured material is not considered credible. Only movement along existing faults is considered.

The evaluation of faulting scenarios depends on the way the faulting affects the repository-performance factors. For example, faulting can affect the ground-water-travel time by modifying existing pathways or by creating new ones. In the extreme case of large-scale movement on a through-going major fault through the repository, the fault could create a direct pathway between the repository and the accessible environment. Strong motion from these types of events could also modify ground-water flow away from the faults, depending on the state of stress, the material properties, and the pore pressure within the affected rock. The ground-water-travel time could be affected by large movements on major faults in the controlled area; in addition, it could be indirectly affected by faulting outside the controlled area if the regional flow is affected.

Fault-induced changes in flow paths could affect the flux of water past waste packages. For example, faulting could occur through the repository and connect transmissive units that are otherwise unconnected. In these instances, an evaluation of increases in the flux through the repository involves consideration of the direction of flow, the permeability of the fault zone and aquifers, the number of waste packages affected by the faulting, and whether the changes are temporary or permanent.

If a faulting event leads to the introduction of new sources of water into the repository and along flow paths, the chemistry of the repository water could be altered. Such alteration could affect the solubility of the waste, the corrosion of the waste package, or retardation along flow paths. Retardation along flow paths could also be affected by physical changes in the fault zone. Finally, the waste-containment time may be shortened if the fault intersects the repository and disrupts any waste packages.

The five categories of faulting considered for the development of scenarios are based on three principal assumptions. First, it is assumed that large events, those capable of rupture lengths of tens of kilometers and displacements of several meters, are considered to be qualitatively different from small events that have rupture lengths of less than a few kilometers and displacements of only a few tens of centimeters or less. For this analysis, a large event is one with a Richter magnitude of more than about 6. Not only are the magnitude and rupture dimensions (length and displacement) of a large event significantly different from those of a small event, the probability of a small event may be many orders of magnitude higher than that of a large event. Second, it is assumed that an event occurring within the repository can have considerably more impact on performance than an event that occurs outside the repository. For example, in addition to impacts on the time of ground-water travel, faulting inside the repository could affect the nature of the host rock and disrupt the waste packages, thereby affecting the containment of the waste. Finally, it is assumed that the events that occur in the controlled area could have different impacts than those that occur outside the controlled area. An event inside the controlled area can have a direct impact on a performance factor (e.g., on the flow paths), while those that occur outside the controlled area would have only indirect impacts (e.g., on the hydraulic-head distributions). On this basis, the categories of faulting scenarios are (1) movement on a large fault inside the repository; (2) movement on a small fault inside the repository; (3) movement on a large fault inside the controlled area but outside the repository; (4) movement on a small fault inside the controlled area but outside the repository; and (5) movement on a large fault outside the controlled area.

For the analysis of these scenarios, the type of information described by Trask (1982) was used to aid in determining faulting probabilities. This information falls into two broad categories: (1) the neotectonic history of the region and (2) data that represent measurements of ongoing deformation.

Specific types of information include an assessment of the state of stress (stress directions and type of faulting expected), measured rates of uplift, subsidence, and tilting; patterns and levels of instrumental and historical seismicity, including published recurrence relationships (see, for example, Algermissen et al., 1982; Bernreuter et al., 1985; Electric Power Research Institute, 1985); and estimated slip rates of faults that have moved in Quaternary time. The applicability of these data is site dependent. Because of the relatively long period of interest (10,000 years), the probabilities assigned to faulting events are likely to be highly uncertain.

Magmatic activity

Magmatic activity is also considered to be a potentially significant disruption to the repository. For example, an extrusive event could exhume a fraction of the waste in the repository during the eruption and entrain the waste in the lava, ash, or gas. However, the most significant release mechanism appears to be entrainment of the waste in the lava and discharge directly to the accessible environment. A less dramatic impact is one in which local temperatures are affected by a magmatic intrusion. Local fluid conditions could be altered, and significant changes in water chemistry could result from the temperature changes. Thus, sorption factors and solubility limits could be affected. Similarly, increased temperatures could affect the rates of waste-package corrosion, decreasing the waste-package lifetime. Furthermore, the increased local temperatures could cause fracturing in the host rock because of thermomechanical or hydrothermal loadings. In this case, in addition to the above thermal effects, fluid movement in and around the repository could be affected by the creation of new ground-water pathways. Geochemical conditions could change if this fracturing allowed the intrusion of new ground water, and possibly corrosive gases, into the repository.

Magmatic activity could have a less direct impact on the repository as well. For example, extrusive activity away from the site could change the surface-water conditions by damming a nearby river. Such damming could result in large-scale flooding that could affect the site. However, the impact of surface flooding on the performance factors was judged to be insignificant for any of the sites. Therefore, the only scenarios that were developed for magmatic activity are concerned with extrusive and intrusive events that directly affect the repository.

C.5.5 HUMAN INTERFERENCE

Disruptions of the repository by human interference have been evaluated many times in the literature (IAEA, 1983; Arthur D. Little Inc., 1980; Cranwell et al., 1982; ONWI, 1985; Harwell et al., 1982; Koplik et al., 1982). Potentially significant human-interference activities that have been considered include both onsite and offsite activities.

Onsite interference

Onsite interference activities are those that would occur in close proximity to the waste-emplacement area and could result in an intrusion into the repository itself (e.g., a borehole passing through the emplacement horizon).

Most onsite activities are regarded as extremely unlikely at a repository site. The period immediately after permanent closure will be one of close technical monitoring and active institutional surveillance. This period will be one in which active institutional control by the Federal Government will provide a highly effective means of precluding potential adverse human activities at the site. For purposes of licensing and safety evaluations (40 CFR Part 191, Subpart B), such active institutional controls are relied on for a period of only 100 years after repository closure. Beyond that period, reliance is placed on passive controls, which consist of (1) a network of permanent markers in and around the site; (2) a variety of permanent records that are deployed by methods designed to perpetuate their existence and availability; and (3) the relatively low natural-resource potential of the site itself, as required by the DOE siting guidelines (10 CFR Part 960, Subpart C). These measures should provide effective protection against inadvertent human intrusions into the repository, particularly those associated with large-scale, protracted activities like solution mining.

This finding has also been made by the NRC and the EPA in their considerations of the potential significance of human interference (10 CFR Part 60 and 40 CFR Part 191, Subpart B). Consequently, the standards regarding such activities do not require the consideration of myriad scenarios for inadvertent human interference. The NRC indicates, however, that occasional penetrations of the repository (e.g., wildcat drilling at the site) over the period of interest must be evaluated. Assumptions that bound the scenarios for these activities have been specified by the EPA in 40 CFR Part 191, Subpart B.

On the basis of the NRC and the EPA regulations as well as the technical studies that form the basis for those regulations, the DOE has developed scenarios for exploratory drilling that include new pathways for radionuclide migration and the direct exhumation of radioactive materials. In the case of the salt sites, these scenarios also consider host-rock dissolution that results from drilling. In selecting the onsite scenarios for more-detailed consideration in this analysis, the DOE was guided by the conditions stipulated in the NRC and EPA regulations; by the physical characteristics of the sites under consideration, as described in the EAs; by the information available in the literature; and by the judgment of technical specialists in the relevant areas.

Offsite interference

Offsite interference includes those activities that could in some way diminish the isolation provided by the repository without physically penetrating the barriers relied on for waste containment or isolation. The offsite activities that have been considered include ground-water withdrawal, extensive irrigation, underground injection of fluids, underground storage of resources (e.g., pumped storage), military activities, and the creation of large-scale surface-water impoundments.

Offsite ground-water withdrawal could be important if the pumping results in a change in the ground-water conditions in the controlled area. However, withdrawal will generally be limited to significant sources of water that are generally capable of yielding substantial amounts of good-quality water and are sufficiently shallow to be economically exploitable. The deep units at the salt sites that might receive radionuclide releases are not likely to meet these criteria. Similarly, while some portions of the geohydrologic system important to waste isolation at the Hanford site may have the potential to be affected by ground-water withdrawal, there is no evidence that withdrawal would actually affect waste isolation either in terms of an effect on the flux through the repository horizon or a significant effect on the ground-water-travel time. With regard to the unconfined aquifer at the Yucca Mountain site, withdrawal from this body is not likely near the controlled area because of the depth to the water table in this area. Although it is possible that withdrawal could occur in the flat areas surrounding the site, such withdrawal should not adversely affect the geohydrologic conditions in the controlled area. This is because pumping from this aquifer would affect an area of only a few hundred meters around the withdrawal point.

Extensive irrigation could eventually affect the geohydrology if the recharge of the deep units is affected. However, Section 6.3.1 of the EAs (DOE, 1986a-e) indicates that, on the basis of the existing geohydrologic data, the potentiometric surfaces of the deep units relevant to repository performance at the five sites would not be adversely affected in less than 10,000 years. Thus, this activity is not likely to lead to a significant disturbance of the repository during the first 10,000 years.

Underground fluid injection could lead to a number of different kinds of disturbances. For example, fluid injection could modify the heads in the receiving unit and those connected to it. The disposal of liquid wastes could alter the geochemical regime within the controlled area. However, the sites appear to have extremely low potential for such injection. The sites were intentionally chosen because of their relative impermeability, and therefore little fluid can be taken up in the units that are important to waste isolation. Furthermore, the sites are remote and offer little incentive over injection closer to the origin of the wastes.

Fluid-injection activities also include offsite hydrofracturing, which could affect the ground-water system. Hydrofracturing has the potential to change some pathways if the fractures propagate into the controlled area. Consequently, the controlled-area boundaries will be selected so that offsite fluid-injection activities will be far enough from the repository to preclude the propagation of hydrofractures into the repository area. This will minimize the impacts of such activities on the site.

Offsite excavation for the storage of resources or pumped energy storage could have an impact if such excavations affect ground-water flow in the controlled area. However, because of the tightness of the formations (i.e., the combination of low permeability and high storativity) needed for storage, impacts on the geohydrology within the controlled area would be negligible. More important, however, is the fact that, as far as is known at present, the formations that are adjacent to each of the sites provide no unique incentives for such offsite excavation. There are vast areas in the region where such excavation could be performed as well or better, and therefore the probability of such activity in the vicinity of the repository is considered to be essentially negligible. Therefore, scenarios for these activities were not developed.

Military activities, such as large-scale weapons testing, could have an impact on site properties. This scenario is important only for the Yucca Mountain site, which is adjacent to the Nevada Test Site. The primary concern is the effects of the seismic wave induced by an underground explosion. However, at Yucca Mountain, explosion-induced disturbances would be much less significant than those from natural seismicity. Therefore, these effects would be bounded by those considered under tectonic disruptions.

The construction of major offsite surface-water impoundments (e.g., reservoirs) that could alter the hydraulic characteristics within the controlled area has also been considered. Surface-water impoundments have potential significance only if (1) the physical conditions in the vicinity of the site are such that the surface-water impoundment could be reasonably constructed (e.g., ability to dam a river), and (2) the aquifers along potential release pathways are such that the deep geohydrologic system would be changed by the construction of the impoundment. The analyses reported in Section 6.3.1 of the EAs lead to the conclusion that such impoundments would be of little consequence in the units where the transport of radionuclides could be important. Consequently, such impoundments would have a negligible impact on expected repository performance at the nominated sites.

C.5.6 PREMATURE FAILURE OF WASTE PACKAGES

Disruptions due to the premature failure of waste packages have also been considered. The performance assessments in Section 6.4.2 of the EAs (DOE, 1986a-e) considered a special "performance-limits" case in which all of the waste packages were presumed to have failed after only 300 years. The results indicate that early failure of all waste packages is not expected to have a significant impact on releases to the accessible environment. It is not difficult to understand the reason for this result. At all of the nominated sites, the expected time of ground-water-travel is on the order of tens of thousand of years. Consequently, the radionuclide-travel time must be long, and the additional residence time because of containment within the waste package of a few thousand years is only a small part of the overall delay. The effects of early waste-package failure are explicitly considered in all the disruptive scenarios in which radionuclide-travel times are significantly reduced. These include the direct-release scenarios for magmatic activity and human intrusion.

C.5.7 INCOMPLETE SEALING OF THE SHAFTS AND THE REPOSITORY

Incomplete sealing or the failure of the seals after closure could result in an increased amount of water in the repository or in a preferential pathway for radionuclide migration. Therefore, a scenario was developed to take into account the failure of seals to perform as designed.

C.6 SELECTION OF POTENTIALLY SIGNIFICANT SCENARIOS

C.6.1 INTRODUCTION

The preceding sections have discussed the conditions, events, and processes that are judged to have a significant probability of affecting the performance of the repository at the nominated sites. In this section, scenarios judged to be applicable to these conditions are defined in terms of the sequences of processes and events that may have potential impacts on performance. In Appendix D, these potentially significant scenarios will be expressed in terms of site-specific characteristics. Values for the performance factors and for the probabilities of the scenarios at each site will be estimated. The estimates may indicate that a scenario need not be considered at a particular site, because of negligible likelihood of occurrence or negligible consequence.

Scenarios were developed in terms of potential impacts on the performance of the repository (i.e., waste containment and isolation). Therefore, the processes and events of concern are those that can reasonably lead to the following types of disruption:

- The release of radionuclides directly into the accessible environment.
- A modification of site conditions such that the expected repository performance is significantly affected.

Scenarios for direct releases of radionuclides into the accessible environment are important because the primary barriers relied on for containment and isolation may be bypassed. The consequences then depend on the fraction of the waste in the repository that is affected by the disruption and the time when the disruption occurs. An event that occurs early (e.g., before 500 years) may be qualitatively different than one that occurs later because the inventory of radionuclides in the waste packages is very high in the early years. The approach taken here is to estimate direct releases for an "early" disruption (i.e., within the near-term thermal period of about 500 years) and for a "late" disruption (i.e., between 500 and 10,000 years). The evaluations of the scenarios in terms of estimated direct releases are likely to be dominated by the assumptions in the scenarios (e.g., the number of packages affected), rather than site characteristics; therefore, the relative merits of sites may be masked. For this reason, a comparison of sites on the basis of direct-release scenarios must be judicious, with due regard for the assumptions in the model.

The second category of disruptive scenarios covers indirect releases to the accessible environment because of disruptions of the engineered barriers and transport through the natural barriers. In this case, the significance of the impacts depends on the site characteristics that influence these barriers. Thus, the factors considered in the evaluation of expected conditions (e.g., waste-package lifetime, rate of waste dissolution, and radionuclide-travel time) are relevant in the evaluation of these indirect-release scenarios. The impacts of the disruptive processes and events on the site characteristics and conditions affecting the repository-performance factors (Table C-1) are then taken into account. For example, a disturbance that changes the expected chemical conditions at the site could lead to increased waste-package corrosion rates and early loss of containment. Likewise, an event that increases the rate of ground-water flow past the waste, such as a disruption that creates a local flow path through the repository, may lead to an increased rate of release from the engineered-barrier system. Changes in regional ground-water-flow conditions, such as fluctuations in climate and recharge, may result in modifications to the hydraulic gradients that control local flow conditions.

In summary, the direct-release scenarios are evaluated in terms of release estimates, and the indirect-release scenarios are evaluated in terms of impacts on repository-performance factors. The scenarios that are evaluated are those that have at least 1 chance in 10,000 of occurring in 10,000 years. Scenarios that are judged to have a lower probability of affecting performance are not considered in this evaluation, unless the impact on expected repository performance is extremely significant.

It is conceivable that scenarios involving combinations of disruptive events may need to be developed. For example, a combination of movement on a large fault and human intrusion at a site could lead to large impacts on site performance. However, if these phenomena are independent of each other, the probability that both occur within the first 10,000 years and lead to impacts on performance will generally be much lower than that for the individual events. Thus, for the disruptive events in which each event has low probabilities, the scenario for multiple independent events will have negligible probability.

There are several ways in which scenarios for multiple events could be significant, however. First, a combination of a disruptive event and expected conditions, such as a fault movement coupled with expected climatic changes, may have a probability that is not negligible. In this case, it is not necessary to develop a new scenario for the combination of events; it is only necessary to consider the full range of expected conditions when evaluating any of the disruptive processes or events.

A second way in which combinations of disruptive processes and events may be significant occurs when the phenomena are not independent; for example, a scenario for causally related phenomena may have a probability not significantly lower than that for the initiating event. A specific example might be a scenario in which human intrusion leads to enhanced dissolution at a salt site. Such common-cause events and processes are taken into account in the specific development of the scenarios.

C.6.2 SCENARIO 1: NOMINAL CASE (EXPECTED CONDITIONS)

It is assumed that the processes operating in the geologic setting during the Quaternary Period continue to operate over the next 100,000 years. The nominal case scenario is based on the existing geohydrology, geochemistry, and rock characteristics and on the changes expected in these conditions because of natural processes, the effects of repository excavation, and the emplacement of heat-generating waste.

The conditions are modified with time because of expected worldwide climatic changes. In particular, it is assumed that precipitation increases over the next 15,000 years. Ongoing erosion and dissolution rates do not have significant effects on performance, and there are no human activities (beyond repository construction and waste emplacement) that interfere with repository performance. For a period of several thousand years after emplacement, the waste packages provide substantially complete containment of the waste. There is no significant leakage through shaft, borehole, and repository seals, and these seals do not provide preferential pathways for radionuclide transport.

The nominal case for the salt sites is slightly different than that for the Hanford and the Yucca Mountain sites. For the salt sites there is no measurable ground-water flux through the host rock. After the emplacement of the waste packages, brine inclusions in the salt migrate toward the packages because of temperature gradients resulting from the heat generated by the waste. This process provides a potential source of water in the neighborhood of the waste package and continues until the gradient diminishes to a low level. Brine may also seep into the repository openings through any interbeds in the vicinity of the repository horizon. The presence of brine in the vicinity of the package leads to the corrosion of package components and loss of containment at some point. After the waste package fails, brine not consumed by corrosion is available to dissolve the waste. The amount of dissolution is determined by the solubility of the waste-form constituents and the radionuclides. Radionuclides dissolved into the brine are considered to be released from the engineered-barrier system. Radionuclides dissolved from the waste are free to be transported into the accessible environment. Since the movement of water through the host rock is negligible, it is assumed that the mechanism for the transport of radionuclides through the salt is diffusion induced by the radionuclide-concentration gradient. This process continues until concentration gradients are negligible or until the radionuclides reach a relatively transmissive unit. In the latter case, the waste is transported by moving ground water to the accessible environment. Heterogeneity may affect the travel time. The retardation of radionuclides relative to the water movement is assumed to be insignificant for the salt sites.

The nominal case for the Hanford and Yucca Mountain sites assumes that there is a measurable ground-water flux through the host rock. The waste packages fail at some point because of corrosion under the thermal, fluid, and chemical conditions expected in the repository. Flow through the repository leaches radionuclides from the waste at a rate determined by the waste form and radionuclide solubility and the flow rate of water in contact with the waste. The radionuclides dissolved into the ground water are then transported advectively by the ground-water through the host rock to relatively transmissive units that transport the radionuclides to the accessible environment. The radionuclide transport depends on the hydraulic properties of the units and the physical and chemical retardation of radionuclide movement relative to the ground-water movement. Again, geohydrologic and geochemical heterogeneities may affect the radionuclide-travel time.

C.6.3 SCENARIO 2: UNEXPECTED FEATURES

The scenario for release because of unexpected features is the same as for the nominal case, except that the conditions that affect release from the engineered-barrier system or transport through the natural barriers are much more extreme than those considered for the nominal case. Unexpected features include those due to excavation and heat-induced subsidence and uplift, undetected geologic features, or other unknown features. These unexpected features introduce extreme conditions with respect to rock characteristics, geohydrology, or geochemistry.

C.6.4 SCENARIO 3: REPOSITORY-INDUCED DISSOLUTION OF THE HOST ROCK

Expected conditions prevail, except that the thermally induced expansion of the overburden results in fracturing and the opening of existing fractures that allow access to the soluble host rock by relatively fresh water from an overlying aquifer. Localized dissolution proceeds, driven by existing hydraulic gradients and flow paths and accelerated by temperature increases due to the waste. The dissolution zone penetrates the host rock and intersects the repository in less than 10,000 years, thereby introducing water into the repository and providing a hydrologic connection between the repository and the accessible environment. Waste-package corrosion, as well as the amount of water available for the dissolution of radionuclides, is increased. Chemical conditions correspond to those associated with brine saturated with dissolved salt rather than to those of the in-situ brine inclusions. The radionuclides can now migrate through the dissolution zone to the overlying aquifer.

C.6.5 SCENARIO 4: ADVANCE OF A DISSOLUTION FRONT

Expected conditions prevail, except that variability in site characteristics results in local dissolution of the salt units at a rate that is accelerated relative to those estimated from regional average dissolution rates. The dissolution front advances and breaches the repository in less than 10,000 years, permitting significant amounts of water to enter the repository and providing a hydrologic connection between the repository and the accessible environment. Waste-package corrosion, as well as the amount of water available for the dissolution of radionuclides, is increased. Chemical conditions correspond to those of brine saturated with dissolved host salt rather than to those of the in-situ brine inclusions. The radionuclides can now migrate through the dissolution zone to the overlying aquifer.

C.6.6 SCENARIO 5: MOVEMENT ON A LARGE FAULT INSIDE THE CONTROLLED AREA BUT OUTSIDE THE REPOSITORY

Expected conditions prevail, except that movement occurs on an existing, large through-going fault that is located in the controlled area but does not intersect the repository. The fault connects transmissive units above and below the repository or may extend to the surface. The rupture length is many kilometers, while displacement is on the order of 0.50 to 2.0 meters. The ground-water-travel time may be decreased. Although geochemical conditions may be temporarily affected if flow is directed across fresh mineral surfaces, any such effect is transitory, and it is assumed that prefaulting conditions are not substantially changed.

C.6.7 SCENARIO 6: MOVEMENT ON A LARGE FAULT WITHIN THE REPOSITORY

Expected conditions prevail, except that movement occurs on an existing large through-going fault that intersects the repository. Waste packages may be sheared. The fault connects transmissive units above and below the repository or may extend to the surface. The rupture length is many kilometers, while displacement is on the order of 0.50 to 2.0 meters. In addition to impacts on the ground-water-travel time, the flux through the repository may be increased, permitting increased dissolution of waste.

C.6.8 SCENARIO 7: MOVEMENT ON A SMALL FAULT INSIDE THE CONTROLLED AREA BUT OUTSIDE THE REPOSITORY

Expected conditions prevail, except that movement occurs on existing small faults that are within the controlled area but do not intersect the repository. The faults are not large in vertical extent and are likely to rupture over only a few formations. The movement connects transmissive units above or below the host rock. There is no connection with the land surface. The rupture length is a few kilometers, while the net displacement is less than about 50 centimeters. The ground-water-travel time may be reduced if the faulting connects the normal receiving units with more transmissive units.

C.6.9 SCENARIO 8: MOVEMENT ON A SMALL FAULT WITHIN THE REPOSITORY

Expected conditions prevail, except that movement occurs on existing small faults that intersect the repository. Waste packages may be disturbed or sheared. The faults are not large in vertical extent and are likely to rupture over only a few formations. The fault movement connects the repository with transmissive units immediately above or below the repository. There is no connection to the land surface. The rupture length is a few kilometers, while displacement is less than 50 centimeters. Flux through the repository may be increased if the faults were previously filled with secondary minerals. The containment of some waste packages may be lost because of damage caused by the faulting.

C.6.10 SCENARIO 9: MOVEMENT ON A LARGE FAULT OUTSIDE THE CONTROLLED AREA

Expected conditions prevail, except that movement occurs on existing large faults outside the controlled area. The length of rupture is tens of kilometers, and displacement is on the order of several meters. The event is large enough to be capable of altering the hydrologic system in the controlled area. In this case, both ground-water travel time and flux may be affected.

C.6.11 SCENARIO 10: EXTRUSIVE MAGMATIC EVENT

Expected conditions prevail, except that magma rises from an underlying source through the earth's crust as a thin, elongated dike. The dike intercepts a fraction of the waste packages, which fail immediately. Waste from these packages is incorporated into the magma. Two time periods are considered for this event: (1) early, within 100 to 500 years after closure, and (2) late, between 500 and 10,000 years after closure. Waste is carried to the surface, where it can be released into the accessible environment by the weathering and erosion of the cooled lava.

C.6.12 SCENARIO 11: INTRUSIVE MAGMATIC EVENT

Expected conditions prevail, except that magma rises as a thin elongated dike from an underlying source through the earth's crust. The dike intercepts the repository and causes sharp temperature increases out to a distance of about 10 meters from the dike, with temperatures in the surrounding rock exceeding 1000°C. Because of the temperature increases, waste packages in the vicinity of the dike can fail early. Dissolution rates for the waste may be increased because of the impacts of these thermal conditions on solubility. The host rock may be fractured thermomechanically or hydrothermally, and the rates of ground-water flow through the repository may be increased in the vicinity of the dike after cooling.

C.6.13 SCENARIO 12: LARGE-SCALE EXPLORATORY DRILLING

Expected conditions prevail, except that large-scale drilling occurs within the controlled area. On the basis of specifications in 40 CFR Part 191, Appendix B, it is assumed that 30 boreholes per square kilometer are drilled through the repository in 10,000 years. For release of radionuclides directly to the land surface, it is assumed that a nearly direct interception of a waste package by an exploratory borehole would be required. The fraction of the boreholes that could contribute to direct release is estimated from area considerations. For example, for vertical emplacement of waste packages, the effective cross-sectional area for the interception is estimated to be about 4 square meters, assuming that the diameters of the waste-emplacement borehole and the exploratory borehole are 2 and 0.25 meters, respectively, and that the effective target area has a diameter that is the sum of these two. For a repository with an area of 8 square kilometers and containing 16,000 packages, the average area per package is 500 square meters. Therefore, roughly 1 percent of the boreholes are close enough to waste packages to allow for direct release to the land surface in this example.

The boreholes may also contribute to release by providing preferential pathways for radionuclides to migrate to aquifers in which radionuclides may be transported to the accessible environment. The fraction of boreholes that could contribute to these indirect-release pathways is also estimated on the basis of area considerations. It is assumed that the radionuclides that would be available for these indirect releases are those found within the waste package or within the disturbed zone around the waste package. The diameter of this disturbed zone is taken to be about three times the diameter of the borehole. Thus, the composite effective diameter of the target zone for the example considered above would be about 7.5 meters, which implies an effective cross-sectional area of about 45 square meters. Therefore, for this example about 10 percent of the boreholes would be close enough to waste packages to intersect released radionuclides. However, not all of these boreholes may provide pathways leading to indirect release to the accessible environment. It is assumed that, for a borehole to provide such a pathway, it must connect transmissive units above and below the repository. About 80 percent of the boreholes are assumed to be deep enough to reach transmissive units 1000 meters or more below the repository horizon. Thus, on the order of 8 percent of the boreholes would provide preferential pathways for indirect releases of radionuclides to the accessible environment in this example. The estimates of actual fractions of boreholes contributing to direct or indirect releases will depend on the site-specific area per waste package.

If pumping is required for a direct release, it is assumed that 200 cubic meters of water is released to the surface per borehole (40 CFR Part 191, Appendix A). The borehole permits water from overlying units to flow through or into the repository, and the waste packages in proximity to the boreholes are assumed to fail immediately. The flow through the borehole provides a source of water for the dissolution of the waste. The water flowing into the repository may have a different composition than water in the host rock under expected conditions; therefore, the change in geochemistry may further affect dissolution rates. The borehole can provide a pathway with a ground-water-travel time different from that under expected conditions.

C.6.14 SCENARIO 13: SMALL-SCALE EXPLORATORY DRILLING

The scenario is similar to that for the scenario 12 except that less drilling is considered. In this case, it is assumed that three boreholes per square kilometer intersect the repository in 10,000 years. All other effects and percentages are assumed to be the same as specified in scenario 12.

C.6.15 SCENARIO 14: INCOMPLETE SEALING OF THE SHAFTS AND THE REPOSITORY

Expected conditions prevail, except that some shafts and tunnels are incompletely sealed. It is assumed that the seals may have an effective conductivity as high as 10 meters per year. This conductivity may permit flooding of the repository and provide a preferential pathway for radionuclide migration to the accessible environment. Because increased amounts of water may be available, waste packages may fail early, and the dissolution of waste may be increased. The time of ground-water travel to the accessible environment may be decreased.

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Appendix D

SITE RATINGS ON POSTCLOSURE REPOSITORY PERFORMANCE

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Appendix D

SITE RATINGS ON POSTCLOSURE REPOSITORY PERFORMANCE

D.1 INTRODUCTION

For each of the nominated sites, the conditions, processes, and events that could affect the performance of a repository were examined (see Sections C.1 through C.5 of Appendix C), and 14 scenarios were identified as having the potential in terms probability and consequences for significantly affecting repository performance. These scenarios are described in generic terms in Section C.6. In this appendix, detailed descriptions of the 14 scenarios are provided for each of the five nominated sites along with estimates of probabilities and scores against the performance measures. The site-specific details for each scenario are based on information given in Sections 6.3.1 and 6.4.2 of the environmental assessments for the nominated sites (DOE, 1986a-e).

The probabilities and scores were assessed by a panel of postclosure technical specialists (see Table A-2), with procedural guidance from members of the methodology lead group (see Table A-1). The process can be summarized as follows. For each scenario at a particular site, one member of the panel presented the site-specific details of that scenario, including any probability estimates from the literature, to the other members. After discussion, each panel member provided best-judgment, high-probability, and low-probability estimates for the occurrence of the scenario during the first 10,000 years after repository closure. The probability estimates were collected, tabulated, statistically summarized, and presented to the panel for discussion. After discussion, the panel arrived at a set of high-probability, base-case, and low-probability estimates for the scenario at a given nominated site. If the high probability was judged to be less than 1 chance in 10,000 over the first 10,000 years, the scenario was dismissed from further consideration unless the potential consequences in terms of releases were estimated to be extraordinarily great. By this process, probabilities were assessed for 13 of the 14 scenarios examined for each site. The probability of scenario 1--the nominal case--was obtained by summing the probabilities of the 13 other scenarios and subtracting the result from unity.

To score a scenario for a given site against the performance measures, one member of the panel presented the site-specific details of that scenario to the other members. After discussion, the performance factors F and T_i were calculated on the basis of agreed-on estimates of the various site characteristics. These characteristics included the median time of ground-water travel, radionuclide-retardation factors, etc., as described in Section B.3.2. After any further discussion was concluded, each panel member provided best-judgment, high, and low scores for the scenario against the performance measures for the first 10,000 years and for the period 10,000 to 100,000 years after closure (Figures B-3 and B-4 and Tables B-1 and B-2). The high score was based on the judgment that the site characteristics and the corresponding release estimates were such that there was only 1 chance in 20 that the actual characteristics and releases would be even more favorable. Conversely, the low score was based on the judgment that the expected site characteristics and corresponding release estimates were such that there was only 1 chance in 20 that the actual characteristics and releases would be even less favorable. The scores were collected, tabulated, statistically summarized, and presented to the panel for discussion. After a period of discussion, the panel recommended a set of high, base-case, and low scores for the site-specific scenario for each performance measure.

Some of the information used to make these judgments is summarized in Tables D-1, D-2, and D-3. Table D-1 lists the information needed to estimate the performance factors for the potential dissolution of radionuclides under expected conditions. This table lists the solubility limits for various radionuclides and the uranium dioxide ceramic waste form. These solubility limits, along with the time-dependent mass fractions given in the environmental assessments and the supporting references, are used to estimate isotope-concentration limits, C_i. The resulting sum of the ratios of C_i to the release limits, RL_i, specified by the U.S. Environmental Protection Agency in 40 CFR Part 191 (EPA, 1985) are also given in Table D-1 as a function of time. These sums, multiplied by the appropriate volumes of water, provide the F factors for use in the evaluation of the sites.

Table D-1. Solubility factors for evaluating potential waste concentration limits at the nominated sites

Element	Solubility limit (ppm)		
	All salt sites[a]	Hanford	Yucca Mountain
C	0.06	0.056	Large[b]
Se	0.001	7.9	--
Sr	0.8	9×10^2	85
Tc	0.001	0.99	Large[b]
Sn	0.0001	1.3	0.00013
I	6×10^5	1.29×10^5	Large[b]
Cs	6×10^5	1.4×10^3	Large[b]
Ra	0.00042	0.24	1.9
Th	0.001	0.23	--
Np	0.001	2.4	720
Pu	0.001	2.4	0.43
Am	0.0001	0.00024	0.0024
Cm	0.001	--	--
Waste form (UO_2)	0.001	0.24	50

Time (years)	$\sum C_i/RL_i$ (per 1000 MTHM/m^3)		
	All salt sites	Hanford	Yucca Mountain
1,000	1.5×10^{-8}	4.2×10^{-6}	5.3×10^{-4}
10,000	3.8×10^{-9}	1.1×10^{-6}	2.2×10^{-4}
100,000	1.6×10^{-10}	4.5×10^{-8}	9.4×10^{-6}

[a]Solubility in water. Values may be smaller in saturated brine.
[b]Solubility controlled by the dissolution of the waste form.

Tables D-2 and D-3 present estimates of the performance factors F and T_1 and pertinent characteristics for each site under expected conditions. Table D-2 gives the estimates for the first 10,000 years, and Table D-3 gives the same information for the period 10,000 to 100,000 years after closure. The values of F are derived from the sums in Table D-1 and the estimated volumes of water available for dissolution. These estimates are explained in the evaluation of the various scenarios described below.

D.2 DAVIS CANYON SITE

Scenario 1: Nominal case (expected conditions)

For the purposes of this analysis, it was assumed that a repository at the Davis Canyon site would be constructed in the Paradox Formation, a thick (about 800 m) sequence of interbedded salt, anhydrite, shale, dolomite, and limestone. The repository would be located entirely within Cycle 6, a salt bed approximately 60 m thick at a depth of about 900 m from the surface. It was assumed that the mined area occupies less than 30 percent of the underground repository area and that spent fuel equivalent to 70,000 metric tons of heavy metal (MTHM) would be distributed in about 16,000 waste packages (4.6 MTHM per package) over a total area of about 8 km^2.

To estimate the volume of water available for waste dissolution in the first 10,000 years after closure, both brine migration and leakage from interbeds or through the shaft and repository seals must be considered. Estimates of brine migration in the salt range between 0.04 to 0.8 m^3 of high-magnesium brine per waste package, which was assumed to be available for waste-package corrosion and waste dissolution. The amount of leakage from interbeds or through the shaft and repository seals is difficult to estimate, but an upper bound can be calculated by considering the available void volume in the repository. This volume is expected to change with time because of salt creep. If the openings are assumed to close to about 1 percent of the excavated void space, the void volume would be 3300 m^3 per 1000 MTHM. This volume therefore represents an upper bound for the amount of brine that could be available for waste dissolution. Estimates of waste-package lifetime range from more than 2700 years for unlimited brine to much longer times for a limited volume of water. The brine available for the dissolution of the waste is estimated to range between less than 170 m^3 per 1000 MTHM to 3300 m^3 per 1000 MTHM. No other significant source of water is expected at the site for the first 10,000 years. As explained in the EA (DOE, 1986a), brine migration is not expected after the first 10,000 years because the thermal gradients that induce this migration will have decreased to negligible levels by this time. Likewise, no additional leakage into the repository from other sources is expected after the first 10,000 years because salt creep will reduce the void space and limit further inflow. Therefore, no additional volume of water is considered for the period 10,000 to 100,000 years after closure.

The concentration limits used in the EA analyses are based on solubility data in the literature and are given in Table D-1. The panel considered the possibility that the values at the site could be as much as 10 times higher

Table D-2. Site characteristics and performance factors for the nominal case for the time period 10,000 to 100,000 years after closure

Parameter	Site: Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
Volume of water available for dissolution of waste, Q (m^3/1000 MTHM)	0 to 3300	0 to 4000	0 to 3300	100,000 to 120,000	0 to 18,000
$\sum_i$ C/RL (1000 MTHM/m^3)	3.8×10^{-12} to 3.8×10^{-8}	3.8×10^{-12} to 3.8×10^{-8}	3.8×10^{-12} to 3.8×10^{-8}	4.1×10^{-10} to 4.1×10^{-6}	2.2×10^{-8} to 2.2×10^{-4}
F	0 to 1.3×10^{-4}	0 to 1.5×10^{-4}	0 to 1.3×10^{-4}	4.1×10^{-5} to 4.3×10^{-1}	0-4
Median ground-water-travel time, T (years)	230,000 to 400,000[A]	45,000 to 170,000[A]	10,000,000 to 35,000,000[B]	22,000 to 83,000	42,000 to 200,000
Retardation, R	1	1	1	1 to 200,000	100 to 1,000
Other travel time (years)	$>10^6$	$>10^6$	--	--	--
Total radionuclide-travel time, T (years)	Very long ($>1.2\times10^6$)	Very long ($>10^6$)	Very long ($>10^7$)	22,000 to 1.6×10^{10}	4.3×10^6 to 2×10^8
Waste-package lifetime (years)	2700 to very long	2700 to very long	4800 to very long	4,500 to 8,500	3,000 to 30,000

[A]Travel time in nonsalt transmissive units.
[B]Based on Darcy flow through salt.

Table D-3. Site characteristics and performance factors for the nominal case for the time period 10,000 to 100,000 years after closure

Parameter	Site: Davis Canyon	Deaf Smith	Richton Dome	Hanford	Yucca Mountain
Volume of water available for dissolution of waste, Q (m^3/1000 MTHM)	0	0	0	18 to 180,000	0 to 100,000
$\sum_i$ C/RL (1000 MTHM/m^3)	1.6×10^{-13} to 1.6×10^{-9}	1.6×10^{-13} to 1.6×10^{-9}	1.6×10^{-13} to 1.6×10^{-9}	4.5×10^{-12} to 4.5×10^{-8}	9.4×10^{-10} to 9.4×10^{-6}
F	0	0	0	8.1×10^{-11} to 8.1×10^{-3}	0-0.94
Median ground-water-travel time, T (years)	230,000 to 400,000[A]	45,000 to 170,000[A]	10,000,000 to 35,000,000[B]	22,000 to 83,000	42,000 to 200,000
Retardation, R	1	1	1	31 to 200,000	100 to 1,000
Other travel time (years)	$>10^6$	$>10^6$	--	--	--
Total radionuclide-travel time, T (years)	Very long ($>1.2\times10^6$)	Very long ($>10^6$)	Very long ($>10^7$)	22,000 to 1.6×10^{10}	Very long ($>4.3\times10^6$)

[A]Travel time in nonsalt transmissive units.
[B]Based on Darcy flow through salt.

and 1000 times smaller than those in the table. The F-factor estimates based on these concentration limits and on the volume of brine that might be available for dissolution are given in Tables D-2 and D-3.

The Paradox Formation is relatively impermeable, with a representative hydraulic conductivity of less than 10^{-6} m/yr. Overlying the Paradox Formation, and more than 400 m from the repository horizon, there are units that are more transmissive (conductivity about 1 m/yr) and could yield some water. Well below the repository horizon (900 m) and separated from it by impermeable units are more-transmissive units (conductivity about 10 m/yr). The gradient between the overlying unit and the underlying unit is downward. Gradients within subunits in the Paradox Formation are not well known and could be up or down. It is difficult to model the geohydrology of these relatively transmissive units, and estimates of the median time of ground-water travel to the accessible environment range between 100,000 and 900,000 years in the underlying units, depending on the distance to the accessible environment. If the distance to the accessible environment is 1 km, the median time of ground-water travel is estimated to lie between 120,000 and 240,000 years. For a distance of 2 km, the median time of ground-water travel is estimated to range between 230,000 and 430,000 years.

The radionuclide-travel time depends on the time of ground-water travel in these relatively transmissive underlying units. The retardation of radionuclide movement relative to ground-water movement is not high for brines, and retardation was neglected altogether in the EA evaluations. In addition to the travel through the transmissive units, the radionuclides must travel through the host salt and the confining layers between the host rock and the transmissive units. The EA for Davis Canyon (DOE, 1986a) estimates that more than 1 million years would be needed for the diffusive transport of radionuclides through 20 m of salt. The travel time through the host salt and other confining layers is therefore estimated to be much longer than 1 million years.

The site characteristics and the resulting performance factors for this scenario are summarized in Tables D-2 and D-3 for performance during the first 10,000 years and during the period 10,000 to 100,000 years after closure. These performance factors indicate that there is a high degree of confidence in the performance of the site. For example, independent of the waste-package lifetime or any other consideration, release to the accessible environment is judged to be insignificant because the median time of radionuclide travel to the accessible environment is estimated to exceed 1 million years because of the containment expected from the salt. On the other hand, even if the concentration limit alone were considered, neglecting any other isolation or containment factors, the total release to the accessible environment is estimated to be less than 1.3×10^{-5} of the EPA release limits. Therefore, even if the radionuclide-travel time is neglected, it is likely that the EPA limits would be easily met. Therefore, it is the judgment that the estimated releases would be insignificant. However, uncertainties in the expected conditions could lead to ranges in the performance factors. Thus, the base-case score is judged to be 10, with a low score of 8, for both the first and the second performance measures.

Scenario 2: Unexpected features

Figure D-1 lists the unexpected features that are considered possible at the Davis Canyon site and the various effects they could exert. The first is repository-induced subsidence and uplift, which could result from the effects exerted on the rock mass above the underground facility by the excavation of the repository and the emplacement of waste. These effects could be so severe, for example, that a pathway extending from the repository facility all the way to the overlying aquifer could be developed. Also, at the margin of the zone of subsidence, offsets could occur, and these offsets could lead to a high-permeability, high-porosity zone extending through all of the overlying sediments. Such a disturbance, if it occurred, would clearly affect the local geohydrologic conditions and the performance of the repository.

Small-scale folding of the type that has been observed for some bedded salts was also considered. However, the panel considered that any effects beyond those considered for the nominal case would be either insignificant or unlikely.

Variations in the sedimentary facies at the site, particularly near the repository horizon, could affect conditions at the site. For example, an overlying interbed may be undetected at a site because of variation between the exploratory boreholes. Such an interbed in the extreme case could provide an insulating layer that affects temperatures near the repository or the strength properties of the rock. These differences, if large, could affect other aspects of the system, such as aspects of the geohydrology or the degree of heat-induced diagenetic effects. If some of the strata pinch out away from the site, estimates based on continuous units may misrepresent the ground-water behavior.

Zones of brecciation due to local dissolution could lead to some effects--for example, on the geohydrologic conditions--beyond those expected at the site. If the zone permits rapid flow of water and if the kinetic effects of the geochemistry are important, the geochemical conditions could be different from the expected range.

If zones of increased porosity are present in the host salt, the rock characteristics and hydrologic properties would be much different from those expected. Brine pockets, either isolated inclusionary pockets or large zones of increased porosity saturated with brine, have not been detected at the site, but, if present, could have important effects because they would provide a source of water not considered before. These pressurized pockets could affect rock characteristics, hydraulic properties and flux, and geochemical conditions. Similarly, pressurized gas pockets could affect the strength properties of the rock.

Undetected fractured brittle beds in the vicinity of the repository could affect the strength of the rock and the hydrologic conditions. Such beds were considered in evaluating the range of expected conditions, but here the concern is for extreme conditions (e.g., a transmissivity or flux that are significantly outside the range considered in the nominal case).

UNEXPECTED FEATURES ↓	ROCK CHARACTERISTICS		GEOHYDROLOGY				GEOCHEMISTRY			
	DRAMATIC DIFFERENCE IN HEAT CONDUCTION	DRAMATIC DIFFERENCE IN MECHANICAL STRENGTH & DEFORMATION	DRAMATIC DIFFERENCE IN GROUND-WATER FLOW MECHANISM	DRAMATICALLY DIFFERENT GROUND-WATER FLOW PATHS	DRAMATIC DIFFERENCE IN HYDROLOGIC PROPERTIES	DRAMATIC DIFFERENCE IN HYDRAULIC GRADIENT	DRAMATIC DIFFERENCE IN SOLUBILITY, LEACH RATE, CORROSION, ETC., DUE TO TEMPERATURE INCREASE	DRAMATIC DIFFERENCE IN GROUND-WATER CHEMISTRY FROM NEW WATER SOURCE	DRAMATIC DIFFERENCE IN LOW-GRADE METAMORPHISM OF ROCK, BACKFILL	DRAMATIC DIFFERENCE IN STATE FROM EQUILIBRIUM TO KINETIC
REPOSITORY - INDUCED SUBSIDENCE/UPLIFT		●	●	●	●	●				
UNDETECTED SMALL-SCALE FOLDING										
UNDETECTED LATERAL FACIES CHANGE	●	●	●	●	●				●	
UNDETECTED BRECCIA PIPES			●	●	●	●				●
UNDETECTED ZONES OF INCREASED POROSITY	●	●			●					
UNDETECTED BRINE POCKETS	●	●			●		●		●	
UNDETECTED PRESSURIZED GAS POCKETS		●								
UNDETECTED FRACTURED NON-SALT BEDS		●	●	●	●					
UNDETECTED SMALL-SCALE FAULTING			●		●					
OTHER	●	●	●	●	●	●	●		●	

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Figure D-1. Unexpected features at the Davis Canyon site.

Although there is no evidence of faulting in the Paradox Formation at the site, particularly in the ductile salt units, the existence of small-scale faults could lead to a different conceptual model of the hydrologic conditions at the site.

Small-scale folding, of the type that has been observed for some bedded salts, we also considered. However, the panel concluded that any effects beyond those considered for the nominal case would be either insignificant or unlikely.

The "other" category includes all other unexpected features that could lead to extreme conditions at the site. This category could include renewed folding or diapirism of the Gibson Dome, for example, or the possibility that there may be some Darcy flow through the salt that is not considered to be credible at present.

Even under these extreme conditions, the releases to the accessible environment were judged to be extremely small. The base-case score assigned to the site is 9. It is based on the prediction that the site would have an extremely small release from the engineered-barrier system and an extremely long ground-water travel time even under these extreme conditions; for example, the presence of undetected dissolution features in proximity to the repository is not likely to simultaneously change these factors significantly. However, the panel could not exclude the possibility of some very small releases under the extreme range of conditions. Therefore, because of the high degree of uncertainty and the difficulty in evaluating the effects of such uncertainties under these extreme conditions, the low-estimate score is judged to be 5. The high score is judged to be 10.

The possibility that the undetected features listed in Figure D-1 exist at the Davis Canyon site is very low, but it cannot be entirely ruled out at present. The base-case probability that these features may exist and that they could lead to the extreme conditions is judged to be about 0.014, with a range from zero to 0.1.

Scenario 3: Repository-induced dissolution of the host rock

The heat generated by the emplaced waste could cause an expansion of the host rock that would extend to adjacent, and more brittle, interbeds. However, at the Davis Canyon site the interbeds that are close enough to the host salt cycle to be affected by thermal expansion are relatively impermeable and are expected to contain little or no water. Thus, the transmission of water from these units is extremely unlikely even if such fracturing of the rock between the repository and the interbeds were to occur. Therefore, this scenario was eliminated from consideration for the Davis Canyon site.

Scenario 4: Advance of a dissolution front

There are two known and two suspected dissolution features in the vicinity of Davis Canyon: the Lockhart Basin, the Beef Basin, the Needles Fault Zone, and Shay Graben. The closest of these features (the graben system) is 16 km from the site. Available data indicate that there are no dissolution features closer to the site. The rate of dissolution associated with these features is unknown at present; however, for the purposes of this evaluation, data for dissolution fronts in other basins can be used. Sixteen investigations conducted at the site of the Waste Isolation Pilot Plant in New Mexico and in the Texas Panhandle have found horizontal dissolution rates ranging between 0.07 and 98 cm/yr. In most of these cases (15 out of the 16), the rate of advance is less than 15 cm/yr. Abundant surface indicators of the dissolution exist even for features with these low rates of advance. In view of the slow rate of advance for these cases and because no surface expression of dissolution is present in the area of the Davis Canyon site, it does not seem likely that any of the dissolution features in the area are migrating laterally at a rate higher than 15 cm/yr. In order for a dissolution front advancing from the nearest dissolution feature to breach the repository in 10,000 years, a dissolution rate more than 10 times would have to be sustained. Thus, this scenario was judged to have a negligible probability of occurrence at the Davis Canyon site.

Scenario 5: Movement on a large-scale fault inside the controlled area but not through the repository

There are no known faults that intersect the repository horizon in the proposed controlled area. Whereas the existence of minor faults that may offset the basement strata cannot be ruled out, no faults that show indications of having the potential for generating a large earthquake (magnitude greater than about 6) appear to be present. The Quaternary fault nearest to the site is associated with Shay Graben, at a distance of about 16 kilometers. Recurrence statistics from Algermissen et al. (1982), adjusted to the size of the controlled area, suggest that the probability of an earthquake with a magnitude greater than about 6 is on the order of 10^{-7} per year. The faulting at Shay Graben may be related to salt dissolution and thus may not be seismogenic. Given the absence of known seismogenic faults at the site and the ductile nature of both the repository host rock and the salt units below the repository, the site-specific probability of large earthquakes is likely to be significantly less than the probability cited above. Therefore, a large movement on an existing large through-going fault within the controlled area at Davis Canyon is estimated to have less than 1 chance in 10,000 of occurring over 10,000 years. Because of the negligible probability of the initiating event, this scenario is not considered credible for the Davis Canyon site.

Scenario 6: Movement on a large fault within the repository

Using analyses similar to those described for scenario 5, a significant movement on an existing large fault intersecting the repository at the Davis Canyon site is estimated to have less than a 1 chance in 10,000 of occurring over 10,000 years. Therefore, this scenario is not applicable to the Davis Canyon site.

Scenario 7: Movement on a small fault inside the controlled area but outside the repository

An assessment of the probability of renewed movement on a small fault involves consideration of the location of known faults in the controlled area, the location of Quaternary faults, the level of seismicity in the geologic setting, and published recurrence statistics for the region of the site. Given the ductile nature of the host rock, the lack of Quaternary faults within the controlled area, and the relatively long recurrence times suggested by Algermissen et al. (1982), small-scale faulting is assumed to occur only in the brittle (nonsalt) stratigraphic units in the controlled area. On the basis of current data, estimates that small movements could occur within brittle rock units below the repository are on the order of 10^{-6} per year (range of 10^{-5} to 10^{-8} per year).

The evaluation of the expected range in median ground-water-travel times takes into account the possibility of fractures within the interbeds and the potential for these fractures to act as relatively high conductivity zones that extend to the accessible environment. If fault movement occurred, these travel times would be representative of the faulted pathways. However, the proportion of pathways with short travel times would still be considered small, and thus the range on travel time considered in the nominal case would not be altered. In addition, the time of ground-water travel through the interbeds may be only a small fraction of the total radionuclide-travel time, given the potential for the exceedingly long (million years) isolation time provided by the host rock. Consequently, renewed movements on small faults in the controlled area are not likely to result in significant releases. Hence, this scenario was not considered for the Davis Canyon site.

Scenario 8: Movement on a small fault within the repository

As in the case of scenario 7, an assessment of the probability of renewed movement on small faults involves consideration of the location of known faults in the controlled area, the location of Quaternary faults, the level of seismicity in the geologic setting, and published recurrence statistics for the region. Given the ductile nature of the host rock, the lack of Quaternary faults in the controlled area, and the relatively long recurrence times suggested by Algermissen et al. (1982), fault movement in the host rock is considered to have negligible probability, and therefore this scenario was not considered credible for the Davis Canyon site.

Scenario 9: Movement on a large fault outside the controlled area

At the Davis Canyon site, there may be evidence at Shay Graben that the magnitude of an earthquake could exceed the magnitudes observed historically. However, a full evaluation of the faults associated with Shay Graben has not been completed, and there is a possibility that observed fractures may be related to salt dissolution rather than seismogenic faults. Although a large event (magnitude greater than about 6.5) cannot be ruled out, no credible mechanisms are known that could significantly alter hydrologic conditions in the controlled area, even under the assumption that such an event occurs. Furthermore, any such fault movement would not affect the expected long isolation time provided by the ductile host rock. Section 6.3.1 of the EA for Davis Canyon (DOE, 1986a) discusses studies showing that changes in the vertical permeability outside the controlled area result in no significant changes to horizontal or vertical ground-water velocities from the repository to the accessible environment. Therefore, this scenario was not scored for the Davis Canyon site.

Scenario 10: Extrusive magmatic activity

There is no known Quaternary volcanism at the site. South Mountain (part of the LaSal Mountains) is the nearest volcanic stock, located at a distance of 43 km northeast of the site. This stock has been dated to be 23 to 26 million years old. The closest Quaternary volcanism, Specie Mesa in the San Miguel Mountains, is 127 km east of the site, outside the geologic setting of the Paradox Basin. Estimates of volcanism indicate an average probability for the contiguous United States of less than 10^{-8} per year (A. D. Little Inc., 1980.) In view of the above information, the probability of volcanism at this site in the next 10,000 years is less than 1 chance in 10,000. Therefore, this scenario is not considered to be credible at the Davis Canyon site.

Scenario 11: Intrusive magmatic activity

This scenario is considered not credible at the Davis Canyon site for the reasons given for scenario 10.

Scenario 12: Large-scale exploratory drilling

It is estimated that, during the past 25 years, 23 wells deeper than 700 m have been drilled in an area of approximately 1600 km^2 encompassing the Gibson Dome area and 7 wells within approximately 10 km of the Davis Canyon site (A. D. Little, Inc., 1980). This number extrapolates to a density on the order of six boreholes per square kilometer in 10,000 years. Considerations that take into account projected drilling practices and hydrocarbon usage lead to a conclusion of a finite probability of some drilling at the site that decreases to less than 1 chance in 10,000 of drilling 30 boreholes per square kilometer in 10,000 years (A. D. Little, Inc., 1980). This estimate does not take into account the presence of permanent markers at the site and societal records. Furthermore, the site does not provide any particular attraction over others in the surrounding area for resource development. Thus, the probability of drilling 30 or more boreholes per square kilometer at the Davis Canyon site in 10,000 years is judged to be less than 10^{-4}. However, the probability of drilling a smaller number of holes at the site may be larger. The base-case probability of any large-scale drilling at the site is judged to be 2×10^{-3}, with a range of 10^{-5} to 10^{-1}. Thirty boreholes per square kilometer in 10,000 years is used as an upper bound for this scenario.

There are two kinds of consequences to be considered: direct releases and indirect releases. Boreholes drilled very close to the waste package could result in a direct release if water brought to the surface is saturated with radionuclides. Since the repository would contain no significant amounts of water before drilling and since any flow in the borehole would tend to be downward rather than to the surface, the only source of such release would be the drilling fluids pumped to the surface. The EPA recommends that 200 m^3 of water per borehole be considered for this purpose (40 CFR Part 191, Appendix B). Using the isotope-concentration limits in Table D-1, the scenario leads to a direct release of about 6.4×10^{-10} of the EPA release limit per borehole. An uncertainty of at least two orders of magnitude should be attached to this value because of the uncertainty in concentration limits and other factors.

The indirect-release pathway has been evaluated for a borehole that is drilled through the repository and connects overlying transmissive units with underlying transmissive units. If the borehole is open and uncased, a maximum flow rate of about 10^5 m^3/yr is predicted (ONWI, 1985). This flow would continue until the borehole sealed itself because of creep in the salt units, resulting in a total volume of water of less than 10^5 m^3. There is, of course, considerable uncertainty in this result because it depends on hydraulic information that is not well known at present and the ability of the overlying aquifer to yield a large amount of water.

If the borehole fills with silt or other material from the overlying, unconsolidated units, the flow rate would be much lower (about 240 m^3/yr is predicted from the conductivity of the material in the borehole, 10^4 m/yr (ONWI, 1985)). At the same time, the material in the borehole could prevent closure because of salt creep. In this case, the flow could continue, which implies that 2.4×10^6 m^3 of water could flow through the borehole in 10,000 years and 2.2×10^7 m^3 in the next 90,000 years. Again, there is considerable uncertainty in these estimates. Not all of this water may be available to dissolve waste. The dissolution of salt at the repository horizon may be limited because the dissolution of salt units above this horizon would cause the water in the borehole to become saturated. Estimates indicate that dissolution would probably not extend to a distance of more than 10 m around the borehole (ONWI, 1985).

In order to provide upper-bound estimates, it is assumed that the hole is filled with silt. Using the total volumetric flow and scaling to provide a volumetric flow per 1000 MTHM, it was estimated that waste dissolution would result in a release of less than 1.2×10^{-4} of the EPA limits in 10,000 years and less than 4.9×10^{-5} in the next 90,000 years. These values would apply for each borehole.

The flow through the silted borehole is insufficient to perturb the velocities in the underlying receiving formations (ONWI, 1985). Thus, the estimated ground-water-travel times in this unit are unchanged from the values for the nominal case.

The repository area at Davis Canyon would be about 8 km^2. Therefore, about 240 boreholes would be drilled through the repository in this scenario. Of this number, less than 8 percent would provide indirect pathways for radionuclide transport and less than 1 percent would be close enough to the waste packages to allow a direct release to the surface. In the evaluation it was assumed that two boreholes allow a direct release. This amounts to a direct release of about 10^{-9} of the EPA limits in 10,000 years with an uncertainty of at least two orders of magnitude.

From area considerations, it is assumed that about 18 boreholes can provide indirect release pathways. The other boreholes would not be sufficiently close to waste packages to affect radionuclide migration. It is difficult to estimate releases in this case because the large delay due to radionuclide travel in the receiving aquifer would substantially reduce the inventories. However, the value of F can be calculated for comparison with the expected scenario. In this case, F has a nominal value of 2.2×10^{-3} for 10,000 years with an uncertainty of at least two orders of magnitude. For the period from 10,000 to 100,000 years, the nominal value of F is 8.8×10^{-4}. The predicted median radionuclide-travel time ranges between 230,000 and 430,000 years in either case.

The base-case score for the site is judged to be 9 for both performance measures. However, when taking into account the uncertainties because of the drilling and the somewhat reduced effectiveness of the concentration limits in constraining releases, the site is judged to have a high score of 10 and a low score of 6 for both performance measures.

Scenario 13: Small-scale exploratory drilling

Since the number of boreholes considered in this scenario is 10 times less than that for scenario 12, the consequences are reduced. The direct releases are clearly insignificant. For the indirect releases, the value of F is 2.2×10^{-4} for 10,000 years and 8.8×10^{-5} for the period 10,000 and 100,000 years. There are large uncertainties in these values because of the estimates for total water volume and waste solubility. The radionuclide-travel time is very long, on the order of a million years. Since the consequences are no greater than those for the nominal case, this scenario was not scored for the Davis Canyon site.

Scenario 14: Incomplete sealing of the shafts and the repository

The probability of incomplete sealing at the Davis Canyon site is very small. None of the units through which boreholes would be drilled would be difficult to seal. Although there is little experience with shaft sealing of the type contemplated for the repository, there is considerable experience with the sealing of boreholes in sedimentary rock. Furthermore, the creep of the salt would help in closing shafts and in sealing them. Therefore, the base-case probability of this scenario's resulting in any release is judged to be 10^{-4}, with a range of 10^{-5} to 10^{-3}.

Failure of the shaft and repository seals would permit water to fill the void space in the repository. For a shaft with a cross-sectional area of 30 m^2 and an average conductivity of 10 m/yr, the saturation of this void space could occur at a rate of about 300 m^3/yr. Thus, the quantity of water that could enter the repository through the sealed shafts could be considerably greater than the amount attributed to thermally induced brine migration. If the void space in the backfilled repository closes only to about 10 percent of the original excavated volume before saturation, the volume available for saturation with brine could be as much as 33,000 m^3 per 1000 MTHM. If this much brine were available to dissolve waste as a result of seal failure, the F value for the scenario would be about 1.3×10^{-4}. The range of uncertainty in this value is at least two orders of magnitude.

Water that fills the repository would not have an opportunity to carry away radionuclides because of the low permeability of the host salt. The natural gradient would not be sufficient to transport waste out through the failed seals. Thus, the travel time would still be very long, on the order of a million years.

With the exception of the possibly larger value of F in this scenario, the impacts are close to those for the nominal case. The increased possibility of waste dissolution, however, does influence the score. The base-case score is judged to be 10, with a range from 8 to 10, for the 10,000-year period, and 10, with a range from 7 to 10, for the period 10,000 to 100,000 years.

D.3 DEAF SMITH SITE

Scenario 1: Nominal case (expected conditions)

For the purpose of this analysis, it is assumed that a repository at the Deaf Smith site would be located entirely within a thick sequence of bedded salt in Unit 4 of the Lower San Andres Formation. The host salt bed lies about 800 m below the surface. It is assumed that the mined area occupies less than 30 percent of the underground repository area and that 70,000 MTHM of spent fuel would be distributed in about 16,000 waste packages (4.6 MTHM per package) over a total repository area of about 9 km^2.

Estimates of the brine migration induced in the salt show that 0.4 to 0.7 m^3 of high-magnesium brine would be available per waste package for corrosion and waste dissolution. Estimates of waste-package corrosion suggest that corrosion will be insufficient to cause any of the waste packages to fail under expected conditions. Even taking into account known uncertainties in corrosion rates, the waste-package lifetime is expected to exceed 10,000 years. Since all brine available from this migration process would be consumed in the corrosion of waste-package components, none would be available for waste dissolution. Other water may be available from seepage through transmissive interbeds. For example, below the host salt is a dolomite interbed that yielded a total of about 80 barrels of brine during 6 months of pumping. If seepage from this interbed into the repository could occur through fractures or anomalies in the salt, additional water would be available. Assuming the openings are backfilled with crushed salt and the creep of the salt results in a final void volume of 1 percent of the original mined openings, the maximum void volume available for water inflow would be less than 4000 m^3 per 1000 MTHM of waste. This quantity provides a reasonable upper bound to the amount of water that could seep into the repository openings. Assuming this amount of water, the waste-package lifetime would not be substantially different from that estimated for the Davis Canyon site (i.e., on the order of 2500 years).

Estimates of concentration limits for the waste-form constituents and the radionuclides are given in Table D-1. Particular values applicable at the site have a range similar to those considered for the Davis Canyon site. The estimated sums of ratios of isotope-concentration limits and EPA release limits are the same as those considered for the Davis Canyon site.

The Lower San Andres Formation is composed of relatively impermeable subunits. For example, the hydraulic conductivity of Unit 4 is probably much less than 10^{-6} m/yr. Other Permian confining units with equally poor conductivity lie above this formation. Very transmissive units that are located above these units are capable of yielding significant amounts of water. These transmissive units are separated from the salt host bed by about 500 m of confining strata. Underlying the host bed is nearly 900 m of lower Permian shale, mudstone, salt, and anhydrite strata with extremely low transmissivities. Below these beds are more transmissive units. Interbeds in the Permian section, such as the dolomite interbed immediately below the host salt, are transmissive in comparison with the salt. The gradients in the Permian section appear to be downward.